



European
Association
Nuclear
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PAEDIATRIC IMAGING

A TECHNOLOGISTS' GUIDE

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Foreword

Imaging of the paediatric population is one of the most specialised areas within Nuclear Medicine (NM), requiring a genuine effort towards a personalised approach and constant adaptation to optimise outcomes while keeping the radiation exposure as low as achievable. This remains a field of great interest, combining the safe application of established paediatric imaging procedures with an ever-evolving landscape. Each year, the EANM Technologists Committee (TC) publishes the Technologists' Guide, offering comprehensive content focused on a specific area of NM practice, with particular emphasis on the practical component of patient care. This year's edition is dedicated to Paediatric Nuclear Medicine Imaging.

Molecular imaging in children remains a bedrock of Nuclear Medicine training, drawing upon the unique physiological, developmental, and clinical considerations associated with these patients. From congenital disorders and inflammatory conditions to nephro-urology, NM often plays a decisive role in the diagnosis, management, and follow-up of a wide range of paediatric diseases. Central to successful imaging is the careful selection of the appropriate pathway, review of protocols and the definition of age- and weight-appropriate acquisition parameters, always with communication and empathy at the forefront. Radiation protection principles remain equally important and merit detailed discussion, and technologists are the key interface with individuals and their families, thus playing a crucial role in informed consent and productive engagement.

Undoubtedly, paediatric molecular imaging calls for a meticulous, patient-centred approach and close collaboration within the multidisciplinary team. Although clinical standards, guidelines, and recommendations may vary between countries, the technologists' role remains consistent and impactful, standing as patient advocates and equipment operators, driving optimisation and ensuring image quality, patient safety, and a positive experience for both children and their families. Thanks to a highly specialised skill set and their ability to balance technical expertise with highly dynamic and interactive environments, technologists leverage their adaptability to achieve the intended results.

This publication proudly gathers contributions from experienced professionals who generously share their knowledge and practical insights into

paediatric nuclear medicine imaging. I would like to sincerely acknowledge all our authors for the time, dedication, and effort they have invested in this valuable work in support of the Technologists' Guide project.

My gratitude also extends to other EANM Committees and their representatives who actively participated in reviewing the chapters, as well as to our colleagues from the Society of Nuclear Medicine and Molecular Imaging – Technologists Section (SNMMI-TS), whose continued support has been invaluable to this project over the years.

I would also like to express my sincere appreciation to the TC members Marta Coelho, Main Editor, Ângelo Cardoso and Tânia Oliveira Hackl, co-editors, for their commitment throughout the preparation of this publication.

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Finally, I would like to thank the Technologists' Committee and the EANM Board for their continued involvement, support, and recognition of the importance of the Technologists' Guide since the inception of this project.

Luísa Roldão Pereira
Chair, EANM Technologists' Committee

Introduction

Nuclear medicine, as a specialised field within medical imaging and therapy, plays a vital role in the diagnosis and management of a wide range of paediatric conditions. Despite its significant clinical value, its application in paediatric patients often requires particular consideration and adaptation, given the unique physiological, developmental, and psychological characteristics of paediatric patients. This edition of the Tech Guide aims not only to review established diagnostic approaches in paediatric nuclear medicine, but also to highlight emerging radiopharmaceuticals and technologies that hold the potential to transform paediatric care.

Advances in nuclear medicine are reshaping the way we approach paediatric diseases, including oncological, neurological, and inflammatory conditions, as well as congenital and metabolic disorders. These innovations offer opportunities for earlier diagnosis, more precise disease characterisation, and targeted therapies. Technologists play a key role in ensuring that these techniques are applied safely and effectively, helping to optimise outcomes while minimising risks.

When putting together this Tech Guide, particular attention was given to the specific challenges of working with paediatric populations. These include radiation protection principles such as dose optimisation, communication strategies

adapted to children and their caregivers, and the importance of creating a supportive and reassuring environment. Ensuring patient safety also extends to careful preparation, appropriate immobilisation when necessary, and the use of child-friendly approaches to reduce anxiety and improve cooperation.

At the heart of paediatric care is a commitment to the child's dignity and emotional well-being. We achieve this by partnering with carers, honouring diverse cultural backgrounds, and ensuring our care plans are flexible enough to support the whole family's journey.

Technologists must be confident in explaining procedures, discussing risks and benefits with parents and implementing tailored protocols that reflect the size,

age, and clinical needs of each paediatric patient. In addition, collaboration within multidisciplinary teams is essential to deliver high-quality, patient-centred care in paediatric nuclear medicine settings.

Working alongside a diverse team of passionate experts, we have produced a comprehensive Guide that is both timely and highly relevant to today's clinical landscape. By integrating health and safety measures, radiation protection and patient-centred practices, the nuclear medicine community continues to advance paediatric healthcare while maintaining the highest standards of informed consent, safety and ethics.

We hope that readers will find this Tech Guide informative, both as a practical tool and as an open invitation to become

involved in these remarkable developments, playing an active part in making these procedures a global reality for paediatric patients.

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Paediatric Patients Are Not Small Adults – Communication Considerations

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EXECUTIVE SUMMARY

The foundational principle of paediatric nuclear medicine is the recognition that children are not merely small adults. Their physiological, cognitive, and emotional development significantly shapes how they experience medical procedures, particularly in the highly sensory and technologically complex environment of nuclear medicine. Many procedures require prolonged immobility, placing considerable demands on a child's limited capacity for self-regulation. Consequently, effective clinical practice requires a specialised approach that balances the technical requirements of imaging with the developmental needs of the child. Integrating principles of developmental psychology throughout the imaging pathway is therefore essential.

Procedural success and image quality are closely linked to a child's developmental stage. Infants require sensory regulation and the reassuring presence of caregivers to maintain emotional stability. Toddlers, as they develop autonomy, may perceive immobilisation as a loss of control and resist the procedure. Pre-school children often engage in magical thinking, which can lead to exaggerated fears if procedures are not clearly explained. School-age children generally seek logical explanations, while adolescents prioritise privacy and respect for autonomy. Failure to adapt communication and preparation strategies to these cognitive profiles can lead to distress, movement, and ultimately to motion artefacts that compromise diagnostic accuracy.

Non-pharmacological strategies — educational, behavioural, and organisational — represent the primary defence against the risks associated with sedation. Although sedation remains necessary

for certain complex procedures such as PET imaging, it carries potential risks including respiratory complications and possible long-term neurocognitive effects. Conversely, shorter procedures such as bone or renal scintigraphy often benefit from non-pharmacological preparation. Educational tools (e.g. explanatory videos or informational websites) and behavioural techniques (e.g. mock scanner training, breathing exercises, and guided imagery) can help children develop coping mechanisms and improve cooperation.

The technical execution of the examination also has psychological implications. Skilled venipuncture and careful radiopharmaceutical administration can significantly influence the child's emotional response. Caregivers also play a critical role, acting as either buffers or amplifiers of anxiety. Clear communication regarding procedures and radiation exposure helps manage caregiver concerns and supports the child's emotional regulation. Ultimately, high-quality paediatric nuclear medicine requires organisational commitment to staff training and child-friendly environments, ensuring a holistic, patient-centred approach that promotes both safety and diagnostic excellence.

Key words: paediatric patients' cooperation; non-pharmacological strategies; child-family-centred communication; developmental psychology; sedation avoidance; environmental adaptation.

INTRODUCTION

Children are not simply “small adults”; their physiological, cognitive, emotional and social development fundamentally shapes how they experience illness and medical procedures. This is particularly relevant in nuclear medicine, as imaging procedures are technologically complex, sensory intense (e.g. PET/MRI) and require sustained immobility. Children's responses follow developmental patterns: infants depend on sensory regulation and caregiver presence; toddlers struggle with the loss of control; pre-school children rely on literal or magical thinking; school-age children seek concrete explanations; and adolescents value autonomy, privacy and respect [1,2]. Frequent misconceptions—such as imagining that scanners “see through” the body or that radiopharmaceuticals “move around inside” — reflect age-appropriate attempts to understand unfamiliar procedures. Across all ages, parental anxiety and beliefs about radiation strongly influence children's emotional responses and cooperation [3,4], underscoring the need for paediatric imaging practices grounded in developmental psychology, family dynamics and age-adapted communication, rather than adult oriented approaches.

This chapter presents a practical, psychologically informed framework for supporting children, adolescents, and caregivers throughout nuclear medicine procedures. It first outlines key psychological determinants of paediatric responses, including fear, anxiety, caregiver influence, developmental cognition, cultural context, and trust. It then describes non-pharmacological strategies—educational, behavioural, and organisational—to reduce distress, improve cooperation, and limit the

need for sedation. Finally, these strategies are applied across developmental stages and procedural phases, from scheduling to post-examination care, to promote a child- and family-centred approach that enhances image quality, reduces procedural anxiety, and improves diagnostic outcomes [3,5,6].

PSYCHOLOGICAL CONSIDERATIONS WITH PAEDIATRIC PATIENTS AND CAREGIVERS

Paediatric nuclear medicine extends beyond technical expertise and requires an understanding of the psychological processes shaping children's emotions, behaviour, and cooperation during imaging [3,6–9]. This section outlines key factors—developmental stage, fear and anxiety, caregiver influence, trust, and cultural context—that underpin effective communication, child centred preparation, anxiety reduction, and successful image acquisition, and introduces the use of nonpharmacological strategies across the imaging pathway (see Figure 1).

Children frequently experience anxiety, fear, and confusion during nuclear medicine procedures due to unfamiliar environments, separation from caregivers, intimidating equipment, and the need to remain still. These reactions—crying, agitation, resistance, or excessive movement—reflect genuine psychological distress and can compromise image quality and safety [7,8]. Responses are closely tied to developmental stage: younger children are more vulnerable to sensory overload and limited understanding, whereas older children and adolescents may experience anticipatory anxiety related to pain, lack of privacy, or diagnostic implications [3,7].

Caregivers act as both buffers and amplifiers of distress. Parental anxiety, particularly regarding radiation exposure and potential clinical outcomes, strongly influences children's emotional regulation and cooperation [6,9]. Growing public concern regarding radiation risks heightens these worries, making clear, accurate, and empathetic communication essential to reassure parents and optimise the child's experience [6].

A psychologically informed approach requires developmentally tailored preparation. Infants and toddlers benefit from caregiver proximity and sensory soothing; pre-school and school-age children respond to concrete explanations, visual supports, and preparatory play; and adolescents require honest information, respect for autonomy and privacy, and involvement in coping decisions. Within this framework, nuclear medicine professionals play a critical role in applying preparation

techniques, distraction strategies, and environmental adaptations to reduce anxiety, improve cooperation, minimise sedation, and enhance image quality [3,6,8,10–12].

Establishing trust through empathetic and respectful communication is central to this process. Validating emotions, offering realistic reassurance, and involving caregivers as collaborative partners aid in fostering a calmer clinical environment and support effective child participation [7,9,13]. Sensitivity to cultural values, family beliefs, and individual temperaments further enables teams to adapt communication and care strategies to diverse families [6].

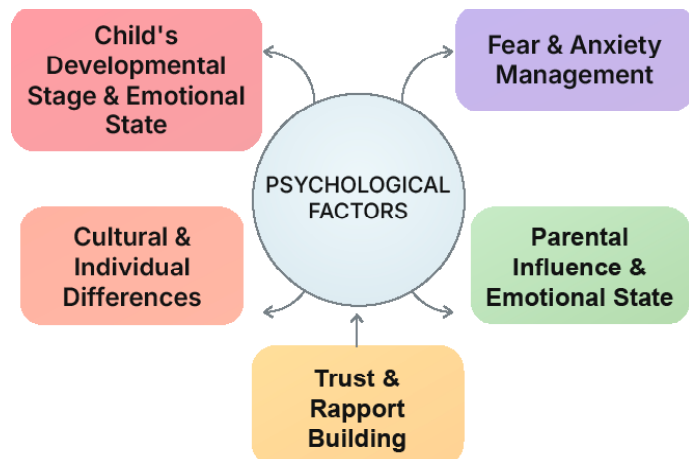


Figure 1.
Core psychological factors influencing a child's experience and cooperation during NM procedures.

EFFECTIVE NON-PHARMACOLOGICAL STRATEGIES FOR ENGAGING CHILDREN

Immobility during image acquisition is a fundamental requirement in medical imaging, with acquisition times ranging from seconds to over an hour. Achieving this cooperation depends on patient comfort, understanding of instructions, and ability to collaborate [14]. In paediatric nuclear medicine, immobility is particularly challenging, as cooperation is closely linked to the child's age, developmental stage, and communication needs. Adapting verbal and non-verbal communication to the individual child and involving caregivers are therefore essential aspects, and effective communication strategies may often reduce or avoid the need for sedation [3,11,12].

Although sedation remains necessary for certain procedures, it should be avoided whenever possible due to associated risks, including hypoventilation, apnoea, airway obstruction, and cardiopulmonary complications [5,15,16]. Early, clear, and developmentally appropriate communication—combined with optimal immobilisation devices and distraction techniques—supports best practice, enhances patient experience, and facilitates high-quality imaging without pharmacological intervention.

Decisions regarding sedation must be made on an individual basis, considering the child's characteristics (such as age and ability to cooperate) and the specific

procedural demands. The decision should be made in consultation with both the NM physician and the referring paediatrician. Longer acquisitions and confined scanner environments, as encountered in PET imaging, are more likely to require sedation than shorter or more open procedures such as renal or bone scintigraphy [6,15,17]. Sedation exists along a continuum from minimal anxiolysis to moderate and deep sedation and general anaesthesia [18]. While anaesthesia is well established, concerns remain regarding potential long-term neurocognitive effects in children [19].

Non-pharmacological strategies are first-line for minimising sedation, prioritising child- and family-centred care by reducing anxiety, improving cooperation, and enhancing image quality through decreased motion artefacts. For nuclear medicine professionals, mastery of these strategies represents a shift from procedural execution to comprehensive patient-centred care [20]. These approaches are commonly organised into three interrelated domains: educational strategies (preparation and familiarisation), behavioural strategies (coping, support, distraction, and organisational strategies (environmental design, scheduling, staffing, and policy), aligning with established paediatric frameworks [3,21].

Educational Strategies

Empowering through preparation and predictable step-by-step scripts for children and families. By transforming an abstract event into a predictable sequence, education promotes a sense of control that is crucial for trust and cooperation.

Information-Based Tools

These tools provide accessible information that explains what will happen before, during, and after the scan.

» Printed and Digital Media:

Illustrated booklets, photo-diaries and short animated videos targeted at different age groups reduce anticipatory anxiety and sedation rates. Studies have shown that providing a photo booklet before a renal scintigraphy significantly decreased children's distress and the need for sedation [22], while a cartoon storybook (e.g. "What is Nuclear Medicine" website <https://whatisnuclearmedicine.com>; Tim and Sunny videos <https://www.youtube.com/@SunnyandTim>) significantly improved a child's ability to tolerate a procedure [6, 23]. Educational videos have been confirmed to increase children's procedural knowledge, reduce anticipated anxiety [24, 25] and improve their overall understanding of the scan [26], with interactive elements further boosting engagement and comprehension.

» Interactive Media and Apps:

Interactive, gamified apps and hospital-produced videos can increase engagement and help families to prepare for the child's examination at home, at their own pace [3; 27; 28].

» Direct Communication:

The preparation process, with pre-exam information, begins during scheduling. Sending clear, concise, age-appropriate

pre-visit information (including feeding/fasting guidance, what to bring, and expectations) allows families to prepare and make necessary arrangements (e.g. bring special toys, books or games, prepare activities for the waiting time) [3,10]. Direct telephone or video contact from a technologist or paediatric coordinator provides opportunity to address caregiver concerns (e.g. radiation exposure, fasting, immobilisation), which in turn reduces caregiver anxiety and indirectly benefits the child [6; 29].

Simulation and Modelling Tools

These tools allow a child to experience the procedure physically or imaginatively in a safe and controlled manner. The three main simulation and modelling tools are mock scanner training, play therapy and pre-scan department tours.

» Mock Scanners:

Ranging from toy-sized models to full-sized replicas, allow children to practice lying still and experience sensory elements in a controlled setting. Studies consistently show a significant reduction in the need for sedation or general anaesthesia [30], whereas others reported a significant increase in the number of children undergoing scans without sedation after mock scanner training [31,32].

» Play Therapy and Role-Playing:

Can be facilitated by paediatricians specialists or trained staff using dolls and role-play to picture and act out the entire procedure. This approach gives children mastery over the sequence of events and dissipates catastrophic fantasies about the procedure [9, 33].

» Pre-Scan Department Tours:

Involve a brief guided tour of the Nuclear Medicine department before the procedure.

This can significantly demystify the environment. Meeting the staff who will be involved and seeing the real scanner can make the setting feel more familiar and the people more friendly, reducing the element of surprise on the day of the exam [3].

Having prepared the child for the procedure, the focus shifts to actively supporting their experience during the scan itself.

Behavioural Strategies

Behavioural strategies give children concrete tasks and coping tools that shift attention away from procedure-related stressors. Their effectiveness depends on

tailoring to age, developmental stage and individual preference.

Relaxation Techniques

These methods are designed to reduce the physical and emotional tension associated with anxiety.

» Structured Breathing:

Child-friendly guided breathing (e.g. "big belly" breathing, paced 4-7-8) is easy to teach. These techniques are widely used in paediatric procedural care and are supported by behavioural pain management literature and evidence-based reviews of non-pharmacological interventions (see Figures 2 and 3) [33].

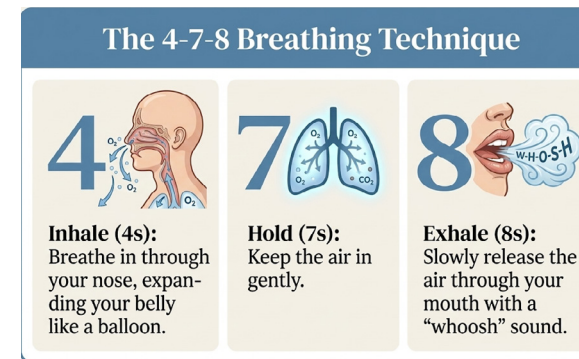


Figure 2.
The 4-7-8 Breathing Strategy.

Five Finger Breathing



Figure 3. Five Finger Breathing: Choose a hand to start and a finger to be your breath pointer (imagine it's a starfish!). Start below your thumb, down at your wrist, and wait for your next in-breath. As you breathe in naturally, trace your in-breath carefully up your thumb with your finger. At the same pace do your out-breath. Do it slowly and then swap hands.
(Adapted from <https://www.goldsmithprimary.org.uk/news-and-events/news-and-blog/relaxation-techniques-for-children-promoting-emotional-awareness-and-regulation>).

» Guided Imagery:

Guided imagery is grounded in cognitive behavioural principles, particularly Beck's cognitive model, which highlights the role of mental representations in emotional regulation [34,35]. In paediatric nuclear medicine, it involves inviting the child to create simple "mind pictures" of a favourite place, activity, or positive story, redirecting attention away from the clinical environment and associated discomfort. By engaging imagination and sensory detail, this technique reduces anxiety and physiological arousal and supports emotional self-regulation during procedures such as injections or prolonged image acquisition. Brief developmentally adapted guided imagery exercises have been shown to reduce distress and improve cooperation in paediatric imaging, especially when combined with calm verbal guidance or breathing techniques [10; 36,37].

Distraction Techniques

Distraction actively focuses the child's attention on engaging stimuli other than the procedure (injection/acquisition) [6]. It can be sensory (bubbles, rattles, light-up toys), visual (ceiling screens, search-and-find books, preferred videos), or auditory (familiar songs, audiobooks, personalised playlists). Cognitive strategies — conversations about hobbies, the "statue game", alphabet categories, counting backwards, or 5-4-3-2-1 grounding (see Figure 4)—redirect attention and reduce anxiety. Systematic and narrative reviews confirm that distraction reduces distress and the need for sedation [8,10]. Age- and interest-tailored interactive methods are most effective, particularly for older children and adolescents [3, 29].

The 5-4-3-2-1 Grounding Technique

A quick guide to this simple sensory method for calming anxious children.



*Figure 4. The 5-4-3-2-1 Grounding Technique: This simple and effective method helps children focus on the present moment by engaging their senses. Here's how it works:
See: Ask the child to name 5 things they can see around them.
Touch: Identify 4 things they can feel, like the texture of their clothes or the chair they are sitting on.
Hear: Listen for 3 sounds, such as voices, footsteps, or a clock ticking.
Smell: Find 2 things they can smell. If nothing is noticeable, ask them to think of their favourite smells.
Taste: Identify 1 thing they can taste, like a mint or the lingering taste of a snack.*

Positive Reinforcement

Rooted in operant learning theory [3], immediate verbal praise and age-appropriate tangible rewards (e.g. stickers, balloons, small toys; certificates of bravery or "superhero" badges) reinforce cooperative behaviours [33,36]. These motivators encourage staying still and following instructions while creating positive associations that reduce anxiety for future visits [33]. The literature recommends announcing clear reinforcement contingencies pre-procedure and delivering praise/incentives immediately post-behaviour for maximum effect [5,22,33].

Organisational and Environmental Strategies

While educational and behavioural strategies are targeted interventions, organisational and environmental strategies are the foundational, system-level adjustments that create the prerequisites for their success. They are the structural bedrock upon which a child family-centred approach is built, embedding supportive practices into the nuclear medicine department's physical space and staff culture [6].

The Physical Environment

» Child-Friendly Decor:

The inherently clinical atmosphere of nuclear medicine departments can intimidate children. Welcoming decorations, colourful wall art, cartoon characters, and soothing ambient lighting in waiting rooms and imaging suites create a significantly

less stressful environment for children and families [5,6,20].

A child-friendly, visually engaging setting—incorporating colourful wall art, ceiling murals, themed decorations, or playful visual elements—helps to shift attention away from the injection or scanning process and reduces fear associated with unfamiliar clinical spaces (see Figure 5). In paediatric nuclear medicine, several departments have successfully integrated cartoon-wrapped gamma cameras, ambient LED lighting, projector animations, and decorated waiting areas, which not only normalise the environment but also support sustained attentional engagement during positioning and image acquisition (see Figure 6) [5,6]. These environmental modifications have been shown to complement behavioural distraction tools, reducing anxiety, motion artefacts and reliance on sedation [3,10] while transforming the imaging suite into an active therapeutic component.



Figure 5. Example of a waiting room with a dedicated paediatric area. Wall painting, toys and games are available, as well as a dedicated sitting area for young patients.



Figure 6. Example of a dedicated gamma camera imaging room for paediatric patients. Colourful wall paintings with cartoons.

» Available Technology:

Nowadays, technological options for distraction are widely accepted and have proven very effective. This option should be carefully considered before being offered considering the family's usual practices regarding technology use. Their effectiveness is likely to be enhanced when these devices are already associated with positive experiences in the child's daily life.

Procedural and Logistical Planning

» Strategic Scheduling:

Thoughtful scheduling is a simple but powerful tool. Paediatric appointments should be planned to minimise waiting times, as long waits can increase anxiety. Procedures that require fasting should be scheduled as early in the morning as possible for the child's comfort. Planned timeslots should be adapted to the paediatric patient, allowing more time than for adults. During a paediatric examination, the patient may be crying and suffering from significant stress. Also, when a scan takes longer than planned, the following patients will be kept waiting longer than they should, thus increasing their stress too [3,6].

» Caregiver Presence and Role:

Nuclear medicine departmental policy should actively encourage a caregiver's presence during the procedure. Moving from passive permission to active involvement, caregivers should be given clear instructions on how they can help, whether by reading a story, holding their child's hand, or providing verbal reassurance, making them a valuable member of the care team. Making a special toy, blanket, pacifier/dummy, etc. available and using it to help calm down

the child is an active role that the caregiver can easily play. This possibility should be mentioned during the scheduling process. Caregiver involvement not only benefits the child's emotional state but also improves cooperation and streamlines the process [33,36].

Staff Training and Communication

» Child-family-centred Communication:

Child-family-centred communication is a cornerstone of high-quality paediatric nuclear medicine practice. Structured, intentional communication throughout the imaging pathway—explaining procedure, timing, radiation safety, and sensations—reduces uncertainty and caregiver anxiety, which directly impacts child distress and cooperation. Frameworks like AIDET® (for a detailed application in NM see table 16.2 in [29]) standardise empathetic messaging about who is involved, what will happen, and duration [6]. Ultimately, the success of a photo booklet or a distraction technique requires organisational commitment to strategic scheduling (minimising wait times), non-intimidating environments, and empowering caregivers as co-regulators through specific guidance on support strategies (what to say, when to distract, physical comfort). This improves behavioural outcomes and reduces distress without extending exam duration [3, 33].

» Specialised nuclear medicine Paediatric Skills:

Paediatric nuclear medicine imaging quality depends on specialised team training. Proficiency in paediatric-specific technical skills—particularly venipuncture, radiopharmaceutical administration, and immobilisation—is critical to minimising

procedural pain, distress, and technical failure. Successful venipuncture — performed by experienced staff using standardised protocols — is an essential step for the overall outcome of the procedure: it ensures predictable activity administration, is critical for quantitative studies such as renograms, and sets an emotional and trustful tone for the exam [6,39].

Equally important is structured training in paediatric behavioural management and communication. Relying solely on individual experience or personal comfort with children is insufficient. Structured Continuous Professional Development (CPD) programmes equip nuclear medicine professionals with validated psychological, behavioural, and communication strategies tailored to different developmental stages

(e.g. how to communicate radiation risk to caregivers and adolescents?). Training in child-friendly immobilisation techniques—using paediatric-adapted cushions, vacuum mattresses, sheets, or mindfully applied straps—helps achieve effective motion control while minimising fear and discomfort. Combined with child-family-centred communication and behavioural coaching, specialised training improves patient welfare, reduces the need for sedation, and enhances image quality and efficiency [6,10, 36, 40].

Non-pharmacological strategies previously discussed in this chapter are summarised in Table 1 as a tool to guide implementation. It provides examples of educational, behavioural, organizational, and environmental strategies.

Educational Strategies <i>Goal: Prepare and familiarise to reduce fear/anxiety</i>	Behavioural Strategies <i>Goal: Actively manage anxiety/discomfort during procedure</i>	Organisational & Environmental Strategies <i>Goal: Supportive child-centred environment</i>
Information-Based Tools <ul style="list-style-type: none"> » Printed/digital media » Interactive apps » Direct communication 	Relaxation Techniques <ul style="list-style-type: none"> » Structured breathing ("big belly", 4-7-8) » Guided imagery (favourite place/story) 	Physical Environment <ul style="list-style-type: none"> » Child-friendly decor » Available technology
Simulation & Modelling <ul style="list-style-type: none"> » Mock scanners (practice lying still in toy/full-size replicas) » Play therapy/role-playing (use dolls/toys and pictures to act out the procedure) » Pre-scan department tours (guided visits to the imaging department to meet staff and see equipment) 	Distraction Techniques <ul style="list-style-type: none"> » Younger: light-up toys, bubbles, familiar songs/videos » Older: books, videos, games » Caregiver involvement: bring favourite toys/books/stories 	Procedural Planning <ul style="list-style-type: none"> » Strategic scheduling » Caregiver presence/role
	Positive Reinforcement <ul style="list-style-type: none"> » Verbal praise » Tangible rewards (e.g. stickers, balloons, certificates) 	Staff Training <ul style="list-style-type: none"> » Child-family-centred communication » Specialised paediatric skills

Table 1. Non-pharmacological strategies in paediatric nuclear medicine.

A Developmental Approach to Nuclear Medicine Paediatric Care

Effective paediatric care requires communication, preparation, and coping strategies to be tailored to the child's specific developmental stage [2,5]. A one-size-fits-all approach is ineffective, as the cognitive abilities, primary fears, and emotional needs of an infant are vastly different from those of an adolescent. The following subsections analyse five key developmental stages, providing a practical guide for the nuclear medicine professional to deliver age-appropriate, compassionate, and effective care for each group.

Infants (0–12 months)

Cognitive & Emotional Profile:

Infants experience the world through their senses and are entirely dependent on their caregivers for security and comfort [1]. Their communication is non-verbal, expressed through cues such as crying, cooing, and body language. They have no concept of time or the reason for the procedure and respond primarily to the immediate environment and the emotional state of their caregivers.

Key Procedural Stressors:

The primary sources of stress for infants are separation from caregivers, unfamiliar environments (cold rooms, bright lights, loud noises), physical restraint, and pain or discomfort from procedures (venipuncture, positioning) without the capacity to anticipate or make sense of them. Disruption of sleep and feeding routines can amplify irritability and movement, making them a clinical challenge. They are highly sensitive to the anxiety of their

parents, which can quickly escalate their own distress.

Recommendations for the nuclear medicine professional:

(1) regulate the environment (reduce light, noise, temperature) to minimise sensory overload, (2) maximise caregiver presence for comfort and containment, (3) align procedures with feeding and sleep rhythms, and (4) interpret crying and movement as distress communication, not “non-cooperation”.

Toddlers (1–3 years)

Cognitive & Emotional Profile:

Toddlers are in the transition from sensorimotor to early preoperational thinking - language develops rapidly, but thinking remains concrete, focused on the present, and increasingly egocentric [1]. They have limited understanding of cause-effect, and difficulty grasping the sequence and purpose of procedures beyond immediate sensations. Toddlers thrive on routine and predictability and have a strong drive for autonomy (“I do it”) paired with fragile self-regulation, often through resistance. Tantrums are common under stress, fatigue or perceived loss of control. They present an inability to tolerate long waiting periods without structured distraction or movement.

Key Procedural Stressors:

Separation from caregivers remains a primary source of anxiety. Toddlers are also highly anxious about unfamiliar people, strange environments and bodily intrusion (needles, immobilisation). Due to toddlers' high sensitivity to perceived loss of control, being held down, strapped or forced to lie still can be experienced as threatening, making this particularly challenging.

Recommendations for the nuclear medicine professional:

(1) maximise caregiver presence to support autonomy and avoid power struggles, (2) use concrete terms (“big camera”, “small pinch”) instead of medical jargon, (3) offer limited choices to support autonomy (e.g. “red sticker or blue sticker?”), (4) ensure predictability with simple “first-then” sequencing, (5) recognise movement as self-regulation rather than misbehaviour, (6) avoid threatening language or bargaining (“if you don't stay still...”), which heightens anxiety and opposition.

Pre-school children (3–5/6 years)

Cognitive & Emotional Profile:

Pre-school children are in the pre-operational stage, during which symbolic play and imagination flourish but thinking is dominated by egocentrism, centration and magical explanations [1]. They cannot yet reason logically, showing difficulty in understanding the need for exams and the various steps involved in them. They show emerging capacities for guilt and shame, and can attribute illness and procedures to punishment, misbehaviour or external agents with intentionality. Therefore, they may silently believe they “deserve” unpleasant procedures. While their language skills are more advanced, they interpret words literally and are heavily influenced by the adults in their lives [29]. They continue to have difficulties tolerating prolonged stillness and separation without preparation and structured support.

Key Procedural Stressors:

Separation from caregivers and the unfamiliar environment (e.g. loud sounds) are still major sources of stress. Fear of bodily harm is a significant concern. Due to

their rich fantasy life, pre-school children's fears may be amplified by imagined scenarios when information is vague or alarming. They may worry that the camera will hurt them or that the injection will “leak out” (e.g. misinterpretations of “special medicine” as something dangerous, poisonous or punitive). The disruption of their normal routines also causes anxiety [29].

Recommendations for the nuclear medicine professional:

Because preschoolers engage in magical and literal thinking, recommendations include (1) avoid technical jargon and emotionally loaded terms (e.g. “radiation”, “dangerous”, “metabolism”) that may fuel catastrophic fantasies, (2) explicitly counter ideas of blame or punishment, emphasising that procedures are to help, not to punish, (3) use simple sensory and procedural information (what the child will see, hear and feel), playbased modelling, and non-threatening metaphors to transform fear into cooperation, especially when combined with familiar comfort objects and caregiver support, (4) integrate medical play (dolls, drawings, play sets) to rehearse the sequence and foster a sense of mastery and (5) maximise caregiver presence as communication/distraction mediators [6].

School-age children (6–11 years)

Cognitive & Emotional Profile:

Children in this stage are concrete operational thinkers, having an increased capacity for logical reasoning about concrete events and internal bodily processes. They are less egocentric and can understand cause-and-effect relationships and simple physiological explanations; they can follow multistep instructions and see the link between

their behaviour and outcomes [1]. They are developing a sense of responsibility, have better verbalisation of feelings and frequently ask questions. They have growing concern with competence, fairness and evaluation. Their understanding of the exam's purpose increases their potential for cooperation. Patients in late childhood may experience shame or embarrassment around body exposure or wearing gowns.

Key Procedural Stressors:

The primary fears for this age group shift toward concrete concerns, including fear of pain (needles, injections), fear of damage resulting from the exam, fear of failing to stay still or “not being brave enough”, and fear of having to repeat the exam. They can show anxiety about the meaning of the exam (how serious is my illness?), even if not explicitly voiced, and have a growing concern about the loss of privacy [29].

Recommendations for the nuclear medicine professional:

(1) provide honest explanations and concrete reasoning about cause and consequence, explaining what the exam shows (e.g. organ function) and why each step (fasting, waiting, stillness) matters, (2) invite questions, correct misconceptions, normalise fear, and offer concrete coping tools, (3) frame cooperation as a skill to practise, promoting engagement, confidence, and sustained stillness during imaging, (4) acknowledge effort and strategy use (e.g. “You used your breathing really well”), not just outcomes and (5) always respect privacy during changing and positioning.

Adolescents (12–18 years)

Cognitive & Emotional Profile:

Adolescents are at a formal operational stage, showing capacity for abstract reasoning, hypothetical thinking and the

integration of complex information. They can understand complex medical concepts, probabilistic risk, long-term consequences and interactions among treatments, lifestyle and prognosis, though this capacity varies widely [1]. During this stage adolescents develop their identity, showing heightened self-consciousness and sensitivity to autonomy, control, privacy, and body image. Emotional responses can be intense; adolescents may oscillate between apparent detachment and strong anxiety or anger. Peer relationships are central, and they are highly sensitive to being treated with respect.

Key Procedural Stressors:

Major stressors include threats to their body image, a profound sense of loss of control over their situation, fear of being patronised or treated like a child, and worries about being seen as “different” or “sick” by peers. Concerns about privacy and exposure are paramount, and they may be anxious about the exam results and how it could affect their life, social interactions and plans (education, work, fertility, relationships). They may also have a fear of radiation and long-term harm, sometimes informed by fragmented or inaccurate online information.

Recommendations for the nuclear medicine professional:

(1) involve adolescents directly in communication and decision making to preserve control and engagement; (2) recognise the adolescent as the primary partner in care, with parents positioned as allies; (3) provide detailed, honest information on procedure, purpose, risks and expectations, using comprehensible risk comparisons; (4) negotiate practical aspects that support autonomy and dignity (privacy when changing, choice of music, brief pauses within protocol limits, clarity

about who receives which results); and (5) avoid empty reassurance or a paternalistic tone [40,41].

CONCLUSION

A developmentally informed, child- and family-centred approach is fundamental to high-quality paediatric nuclear medicine imaging. Paediatric practice requires more than technical adaptation: it demands a conceptual shift that recognises the child as an active participant with age-specific reasoning, emotional responses, coping strategies, and rights. Nuclear medicine professionals must interpret behaviour through a developmental and psychological lens and integrate emotionally informed, ethically sound, and culturally sensitive practices at every stage of the imaging process.

Understanding how children think, feel and cope across development stages supports the use of educational, behavioural and organisational nonpharmacological strategies that reduce distress, enhance cooperation, improve image quality, and foster trust. Beyond age, prior medical experiences, family dynamics and cultural background, these factors shape children's perceptions of procedures and stressors, making personalised, responsive care essential. These competencies require structured training, reflective practice and ongoing professional development, affirming paediatric nuclear medicine as a specialised field in which psychological expertise and child- and family-centred communication are critical to the success of every examination.

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APPENDIX

Figure 1. Image created using ChatGPT (OpenAI, 2026). Prompt: Create a clean, professional infographic for a scientific textbook with a central node labelled "Psychological Factors" connected to five surrounding components: Child's Developmental Stage and Emotional State, Fear & Anxiety Management, Parental Influence & Emotional State, Trust & Rapport Building, and Cultural & Individual Differences. Use pastel colours, rounded rectangles, curved arrows and a publication-quality layout suitable for a medical textbook.

Figure 2. Image created by Gemini AI (Google, 2025), from a prompt to create an infographic of the 4-7-8 breathing technique, with illustration and instructive text.

Figure 3. Adapted from <https://www.goldsmith-primary.org.uk/news-and-events/news-and-blog/relaxation-techniques-for-children-promoting-emotional-awareness-and-regulation>

Figure 4. Adapted from <https://www.goldsmith-primary.org.uk/news-and-events/news-and-blog/relaxation-techniques-for-children-promoting-emotional-awareness-and-regulation>

Figure 5. Image created with Gemini AI (Google, 2025), Prompt: A high-quality, professional architectural visualization of a modern paediatric waiting room, with underwater theme.

Figure 6. Image created by Gemini AI (Google, 2025), Prompt: A professional architectural and medical visualisation of a paediatric gamma camera imaging room. The central focus is a modern gamma camera machine, brightly decorated with child-friendly decor. A child is lying comfortably on the imaging bed, positioned correctly for a scan. A female technologist in blue patterned scrubs is standing close to the child, leaning in with a kind expression to provide comfort and adjustment.



Radiation Protection Considerations for the Paediatric Patient

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EXECUTIVE SUMMARY

In paediatric nuclear medicine, certain factors must be taken into account regarding the radiation exposure of patients and other people. These factors include the possibility of more prolonged and/or closer contact with others compared to typical adult patients, an increased contamination risk, and a reduced ability to comply with instructions during diagnostic scans and therapy-related procedures. Departmental procedures and practice must be reviewed to assess their suitability for paediatric patients and adjusted as needed to ensure radiation protection is adhered to while providing excellent patient care.

Key words: Radiation exposure; contamination; carers; restrictions; risk assessment; optimisation; paediatrics

INTRODUCTION

The overarching principle of radiation protection is to minimise the likelihood and/or severity of harmful effects of ionising radiation by minimising and/or limiting exposure to people and the environment. In nuclear medicine, optimisation means balancing some necessary radiation exposure, to the patient and often to other people as well, against the need to achieve the clinical goal.

While this radiation protection principle applies equally to patients of all ages, appropriate practice is likely to differ between adult and paediatric patients for biological, social, and behavioural reasons. This chapter discusses some of the main factors which typically need to be approached differently when caring for paediatric patients. Consideration is given to the protection of the patient, their carers,

clinical staff, and other persons they may come in contact with.

RADIATION RISK AND AGE

Ionising radiation can cause damage to living cells, on a molecular level, by ionisation of the atoms it encounters along its trajectory. This may lead to reversible effects on the cell (for example, if DNA is damaged but repaired correctly), but it can also cause the cell to die (not necessarily immediately) or to survive and proliferate with a DNA mutation. Both of the latter can result in a health detriment [1].

Effects resulting from cell death are referred to as tissue effects, previously called and mostly known as deterministic effects. They are only expected to occur once a threshold absorbed dose is reached; the higher the dose rises above the threshold, the more severe the effects. Effects resulting from cells surviving with DNA mutations are referred to as stochastic. The widely accepted model for the relationship between absorbed dose and stochastic effects is the linear no-threshold model, which posits that any non-zero dose might cause a health effect, and the probability of the effect increases linearly with absorbed dose [2]. The main example of this is radiation-induced cancer, which can take many years to develop from an initial cell mutation [3].

These effects are relevant in all nuclear medicine procedures, but it is important to note that children can be more susceptible to them than adults. Multiple factors influence a cell's sensitivity to radiation, one of which is its cell cycle phase. When a cell is in the pre-mitosis or mitosis phase, it is more sensitive to harmful effects from radiation. This is due to any DNA damage being incorrectly repaired, leading to

cell mutation and/or cell death [4]. Cells undergoing frequent mitosis, as happens in children growing, are therefore more radiosensitive. Children exposed to ionising radiation are also likely to live longer following the exposure than adults, allowing more time for surviving mutated cells to develop into cancer [5].

The risk of radiation-induced cancer is often given as being around 5% per Sievert (Sv) effective dose [6,7]. This is an average across different procedures, genders and age ranges, and is extrapolated from data at higher absorbed doses than those associated with diagnostic nuclear medicine procedures. It can be a helpful tool for putting radiation risks into context but is highly unlikely to reflect the risk to a given individual. In children, the estimated risk can be much higher – up to around 20% per Sv [7]. The adoption of the averaged risk factor in local calculation and communication of risk/benefit may be acceptable, but its limitations must be clarified, particularly for anyone justifying nuclear medicine procedures in children.

It is worth bearing in mind that the absolute risks associated with diagnostic nuclear medicine procedures are still low [8]. However, therapeutic nuclear medicine necessarily involves higher absorbed doses as its aim is to reach the tissue effect absorbed dose threshold to kill tumours or other target cells. In therapeutic nuclear medicine procedures the increased risk to children from absorbed dose to non-target tissues is therefore more important to consider.

OPTIMISING PAEDIATRIC PROTOCOLS

All exposures in nuclear medicine must be optimised – i.e. the absorbed dose to tissue should be kept as low as possible while still achieving the clinically-required result. Multiple factors influence the absorbed dose from a nuclear medicine procedure, including patient anatomy, physiology and the type and activity of radiopharmaceutical administered [9].

Optimisation for paediatric procedures should be considered separately from adult protocols due to differences in anatomy and physiology [10]. EU directive 2013/59 explicitly mandates that member states use “appropriate” equipment and techniques when children are exposed to radiation.

For a given administered activity, the effective dose received by a patient is inversely related to their weight. Additionally, the detected count rate will be higher when there is less tissue to attenuate the gamma photons. Therefore, for children who are smaller than a typical adult, lower activities should be used to keep effective doses low, and this should not reduce the count rate to the extent that image quality is unacceptably deteriorated [9]. Published guidance on recommended activities for paediatric imaging, such as the EANM's paediatric dosage card, provides baseline activities and weight-based scaling factors [11]. Further local optimisation measures can also be developed, such as reducing scan duration while keeping administered activities low, to reduce movement artefacts which deteriorate image quality. This is very important in paediatric imaging, as a shorter scan is more likely to be completed successfully and lead to a better patient experience. The relative importance of

reductions in administered activity and scan duration should be carefully considered, with insight from radiographers and technologists on the practical impact.

In hybrid imaging, the computed tomography (CT) parameters used directly influence patient effective dose. For scans of most children, who are smaller and therefore less attenuating than adults, parameters can be adjusted to reduce effective dose while still obtaining acceptable image quality [12]. Paediatric CT optimisation should be performed, ideally using anthropomorphic phantoms simulating a range of likely paediatric patient sizes. Any automatic dose reduction software should be tested on such phantoms to verify its suitability across the full range of patient sizes.

Optimisation of paediatric exposures is covered in detail as the sole topic of a chapter in a previous EANM Technologists' Guide on radiation protection and dose optimisation [13].

CLOSE CONTACT

Following radiotracer administration, patients may need to follow restrictions on close contact with others due to their external exposure. Children are likely to have more prolonged close contact with other people, including their carers, siblings, other family members, friends, and classmates. Restrictions designed for adults can be unsuitable, and more realistic contact patterns should be used when devising restrictions and providing radiation protection advice [14]. This is even more important for therapeutic exposures.

Paediatric care often involves more prolonged close contact between patients and staff than adult care. Nuclear medicine staff should receive training on the risks

posed by patients' external exposure when working with paediatrics, and training should also include information on special radiation protection considerations required within this cohort. Standard training on minimising time, maximising distance and using shielding still applies, although this can be challenging to adhere to. Staff may need to spend more time performing an administration as well as positioning, immobilisation and distraction during scanning, so identifying opportunities to increase distance can be vital.

If a paediatric patient will be interacting with staff outside of the Nuclear Medicine department, such staff must also receive training at a level appropriate for this interaction and be given contact details for support. This can include staff in anaesthetic teams, play teams, domestic teams, and on wards, some of whom would typically have prolonged close contact with the patients.

CONTAMINATION

Nuclear medicine patients' bodily fluids will usually become radioactive, although the extent of this and the proportion of radioactivity in different fluids can vary. In paediatric procedures the risk of contamination is generally higher, as young patients may not yet have control of their bladder or bowels and may also be less able to communicate if they are at risk of incontinence or vomiting. Additionally, in children, contamination incidents usually involve more people, e.g. their carer, who will be responsible for managing cleaning/decontamination.

While imaging, it is recommended to use absorbent pads and/or waterproof coverings on relevant equipment such as gamma camera heads and beds, to avoid

disruption to the service and enable easier clean-up. Additionally, it can be useful to have spare scanner mattresses available so that staff can remove one which is highly contaminated and immediately replace it with a clean mattress, rather than spend time, increase effective dose, and risk contaminating themselves during decontamination attempts.

The patient's carer should also be given advice on how to handle such fluids safely. This can include using PPE to avoid direct contact with skin, thorough hand-washing techniques, appropriate segregation of waste into an outside bin, and washing contaminated clothing or bedding separately.

Children with little or no control over their bladder or bowels should present in a nappy, as this aids in containing the immediate contamination risk. Carers should be advised to change soiled nappies promptly, to avoid radioactive contamination staying on the patient's skin and reduce the patient's absorbed dose. Additionally, specific instructions on nappy changes should be given, such as placing the new nappy onto the patient immediately after removing the used nappy to reduce the likelihood of contamination. It is important to give this advice before administration as nappy changes may take place at any point.

For inpatients, contamination risk is likely to necessitate specific procedures to minimise the risk of unnecessary exposure to staff and loss of control of radioactive material. Such procedures should be determined in a radiation risk assessment, but will likely include segregation of waste contaminated with patient bodily fluids, such as nappies. Radiation protection training can be shared across the hospital to aid staff understanding of risks.

CARERS & COMFORTERS

Almost all paediatric patients will require a carer and comforter, defined in the European Council Directive 2013/59/Euratom [15] as a person who knowingly and willingly undergoes exposure to ionising radiation to support the patient. Local procedures must clearly outline how carers and comforters are identified and managed.

Potential carer and comforter effective doses should be calculated and suitable mitigations planned, minimising these doses in line with carer and comforter effective dose constraints. These will differ by procedure and, notably in paediatric patients, by age. Younger children are likely to require prolonged close contact and care involving possible contact with radioactive bodily fluids, leading to higher potential carer and comforter effective doses. Mitigation measures must be proportionate to the radiation risk and take account of their impact on the carer and comforter's ability to provide practical and emotional support to the patient.

Children may also need the carer and comforter to remain in the room during a CT exposure as part of a hybrid scan. Appropriate procedures must be available to ensure they are realistic. Collaboration between technologists, radiographers and physicists is recommended to effectively minimise the carer and comforter's effective dose. A key consideration is the best position for a carer and comforter to sit or stand during exposure, as the effective dose rate outside the CT scanner bore can vary greatly with position [16].

From a radiation protection perspective, eligibility criteria to act as a carer and comforter can be decided locally, with the involvement of the staff who will be justifying carer and comforter exposure.

Key considerations include ensuring that a carer and comforter is able to knowingly and willingly accept radiation risks, which can involve an age or competence criterion, and establishing a policy on pregnancy in carers and comforters. As advised in European Council Directive 2013/59/Euratom [15], radiation protection of a foetus should be comparable to that of a member of the public. As the foetus is unable to be knowingly and willingly exposed to radiation, the relevant dose limits and constraints for members of the public should be used.

In a practical sense, the expectation that patients will have a carer and comforter means that facilities to accommodate them should be provided. In an outpatient setting, this includes toilets in the department not used by radioactive patients, or at least knowledge of where the nearest non-controlled toilets are. With paediatric inpatients, a carer and comforter will be expected to stay in hospital with them, and suitable facilities are required to ensure radiation protection is upheld. This is a significant consideration for therapeutic procedures, and is discussed further later in this chapter.

In a broader sense, providing support and reassurance to the carer and comforter also forms part of good radiation protection practice. A carer and comforter who feels involved and understands the purpose of the scan and the advice they have been given will be in a better position to keep their own dose low while supporting the patient to achieve the clinical aim of the procedure.

PREGNANCY ENQUIRIES

The possibility of pregnancy must be established for all patients undergoing nuclear medicine procedures: this can range from verbal enquiries to pregnancy

testing. Usually, an age range forms part of the criteria used to establish whether or not a patient has the capacity to become pregnant and therefore whether further enquiries are needed. This age range can differ, but it will include paediatric patients.

Some paediatric patients, or their carers, may find discussion of pregnancy to be confusing or distressing. Additionally, last menstrual period (LMP) can be unreliable in paediatric cohorts due to irregular cycles. It is recommended to explain that there are radiation risks to the foetus, as this allows the technologist/radiographer to contextualise pregnancy enquiries. Providing information leaflets prior to the appointment explaining that pregnancy enquiries will take place can be useful in minimising discomfort around questioning.

Local pregnancy-checking procedures must be in line with local legislation and statutory guidance and be proportionate to the potential radiation risk. For diagnostic procedures, which would result in low absorbed foetal doses, the patient must be made aware of the risks to a foetus and be given the opportunity to disclose pregnancy or potential pregnancy. For higher-dose procedures such as therapies, more robust methods such as pregnancy testing should be used.

Finally, the presence of the carer and comforter can be complicated, as some patients may be reluctant to discuss this topic or disclose their pregnancy status in front of them. On the other hand, others might be upset about being separated from them for these enquiries. The best approach will vary between patients and will require sensitivity and alertness on the part of the operator, but a documented procedure should be in place to ensure consistency and a minimised risk of accidental foetal

exposure. Additionally, if paediatric patients are pregnant or potentially could be, involvement with safeguarding teams is essential and escalation processes should be in place to ensure the safety of the patient.

ADMINISTRATION TECHNIQUES

Paediatric administrations often need to be approached in a different way from those in adults and often carry a greater risk of radiation accidents.

In intravenous (IV) administrations, children may find the use of a needle frightening and be more likely to move or try to move [17]. Accessing smaller veins can also be more difficult. These factors increase the risk of extravasation, contamination, and needlestick injuries. Suitable procedures for IV administrations to children must be devised to minimise these risks, and must be included in the training procedures for relevant staff. This may include having two members of staff performing each administration: one to hold and distract the patient preventing dislodgement of the needle or IV line, and the other to safely administer the radiopharmaceutical.

Consideration should be given to the method of IV administration: venous cannula or a winged infusion needle (butterfly) can be used. Cannulas can be sited prior to the procedure, minimising potential radioactive contamination; however, thorough flushing must be done to ensure correct siting and prevent extravasation. Butterfly administration can be easier on smaller veins, as well as being less invasive. In some radiopharmaceutical administrations, long central lines can be used:

however, the physical properties of the radiopharmaceutical must be considered to avoid adherence of tracer to the inner walls of these longer lines. Staff expertise in gaining paediatric IV access should be sought before agreeing on suitable methods to be used.

Topical anaesthetics can also be used to reduce injection pain, reducing the risk of movement and improving the patient's experience. Distraction techniques, such as using books/videos to obstruct the view of the IV, can help patients remain calm during administration. In neonates, sucrose solution can be used to minimise the pain of IV procedures. This can either be placed directly on the patient's tongue or applied to a dummy during IV insertion.

In oral administrations, patients should be assessed to ensure they are able to swallow capsules. This is to minimise the risk of unnecessary absorbed dose to the mouth, incomplete administrations, and possible contamination issues. Departments could consider keeping sweets of a similar size and shape to the radioactive capsule and asking the patient to practise the procedure with these first.

STAYING STILL FOR IMAGING

A major challenge for paediatric patients is keeping still during imaging. This is a radiation protection concern, because if a good-quality scan cannot be achieved, the patient will have received an effective dose for no clinical benefit. Creating an appropriate environment for paediatric patients is essential to improve their ability to comply with instructions such as keeping still, thus improving their experience. The EANM procedural recommendations

for managing the paediatric patient in diagnostic nuclear medicine provide detailed advice on how this can be achieved [18].

To support children in the scanning room, staff or a carer and comforter often stay close to the patient for a prolonged period. This should be risk-assessed for all procedures in which it might be necessary, and training given to those supporting the patient on appropriate methods to minimise their effective dose.

Specialised paediatric immobilisation devices can be used, such as the MedVac® vacuum splints [19]. It must be confirmed that these devices do not contain parts which will interfere with the scan by excessively attenuating gamma photons or, in hybrid imaging, the x-ray photons used for CT.

For some scans, sedation may be required to keep the patient sufficiently still. This must be considered on a case-by-case basis, and only used when necessary due to potential clinical risks to the patient [17]. Radiation protection considerations should be borne in mind with regard to involvement of other staff groups needing radiation protection training, use of other departments' equipment requiring contamination monitoring before leaving the department, and the potential for deterioration of a radioactive patient. A contingency plan for patient deterioration should be drawn up and practised.

PAEDIATRIC THERAPIES IN NUCLEAR MEDICINE

In therapies, the typically higher administered activities and longer radionuclide half-lives result in therapy patients posing a greater expected external

exposure risk to others for a longer time period.

One common effective dose mitigation measure is minimising the time spent with the patient. For paediatric patients who cannot be left alone, practical advice on minimising time with the patient could include the possibility of sharing caring duties between multiple people. If this will involve carers not present at the patient's appointment, any radiation protection measures should be communicated to them, and consideration should be given to whether they need to receive formal information or training.

Maximising distance from the patient can be very challenging for both patients and carers, particularly for younger children or those with higher support needs. The emotional impact must also be considered. Pragmatic advice can include:

- » If it is not feasible to avoid hugging altogether, frequent short hugs are preferable to prolonged cuddling.
- » If the carer would usually carry the child when walking along, including to travel around the hospital, using a pram is preferable.
- » Interactions and play which inherently involve distance (e.g. playing catch or sitting apart to play a video game) are ideal to minimise effective dose to the carer or comforter while maintaining normalcy.

When determining and explaining the contact restrictions required upon discharge, the ability of the patient and their close contacts to follow them must be considered. For example, a radioactive inpatient may need to remain in hospital for longer if they have siblings at home from whom they will not realistically be

able to distance themselves. Similarly, patients may need to delay returning to school due to radiation restrictions. Detailed discussion of restrictions in advance of the therapy will allow the patients and carers to prepare for this and minimise disruption to their lives. These discussions should involve the patients, where appropriate, and their carers. Communication techniques may need to be adapted to enable patient understanding. Relevant legislation should be consulted to ensure that any legal requirements for the provision of this information are adhered to.

Contamination with therapeutic radionuclides has the potential to lead to higher effective doses, due to the type of radiation used in therapies compared to diagnostic procedures. The longer physical half-lives of most therapeutic radionuclides mean that contamination will persist for longer if not removed, and contaminated waste will need to be stored for longer to decay to an acceptable release level before disposal. Storing bodily fluid waste, such as nappies, for long periods of time may require additional facilities. Freezers are useful to avoid the waste becoming putrid, or a macerator could be installed to facilitate immediate disposal of contaminated nappies. It may also be helpful to obtain a dedicated washing machine to wash contaminated soiled linen and reduce the need to store it for a long period of time. Any appliance such as a macerator or washing machine must have suitable plumbing arrangements to remove and dispose of radioactive liquid waste via drains – prior to its instalment, advice must be sought from medical physicists with relevant expertise.

Paediatric inpatients are likely to bring toys with them. Contamination of such toys can be significant if a patient constantly

cuddles or chews them, and it can be very hard to remove from soft or textured toys. In an ideal scenario, highly contaminated items would be left in the Nuclear Medicine department and allowed to decay before being returned to the patient or being disposed of appropriately, thereby minimising the risk of radiation exposure. However, withholding a child's toy is likely to upset them and should be avoided. The contamination risk should be discussed with the patient's carer(s) or guardian before the procedure, and an appropriate plan formed: this could include bringing an alternative toy that may be left behind, or seeing if the child can manage without touching the toy during their main excretion period to limit contamination risk.

For any inpatient stays, a lot of attention must be given to creating a comfortable environment. Advice should be sought from the play team on suitable toys, games, and other entertainment devices that can be used for the patient's room, and from the relevant medical physics team on radiation protection implications, such as ease of decontamination.

In inpatient therapy suites, room design must incorporate suitable separate sleeping arrangements, any necessary shielding, separate toilets and appropriate radioactive waste disposal facilities. Room design should also facilitate interactions between the patient and their carer where distance and shielding can be maintained, and these should allow for realistic compliance. For example, it is not realistic to expect a paediatric patient to remain on the opposite side of a closed, opaque lead door to their carer for prolonged periods. Instead, consideration should be given to the use of lead glass windows between the patient and carer areas, and/or mobile

lead shields to provide protection without impeding social contact. Carers must be given detailed training on minimising their own effective dose, including staying out of the patient's room when they don't require support, e.g. when sleeping. They should also wear a dosimeter to allow comparison of their estimated effective dose with local constraints and to identify situations in which carers receiving high doses may benefit from further radiation protection discussions.

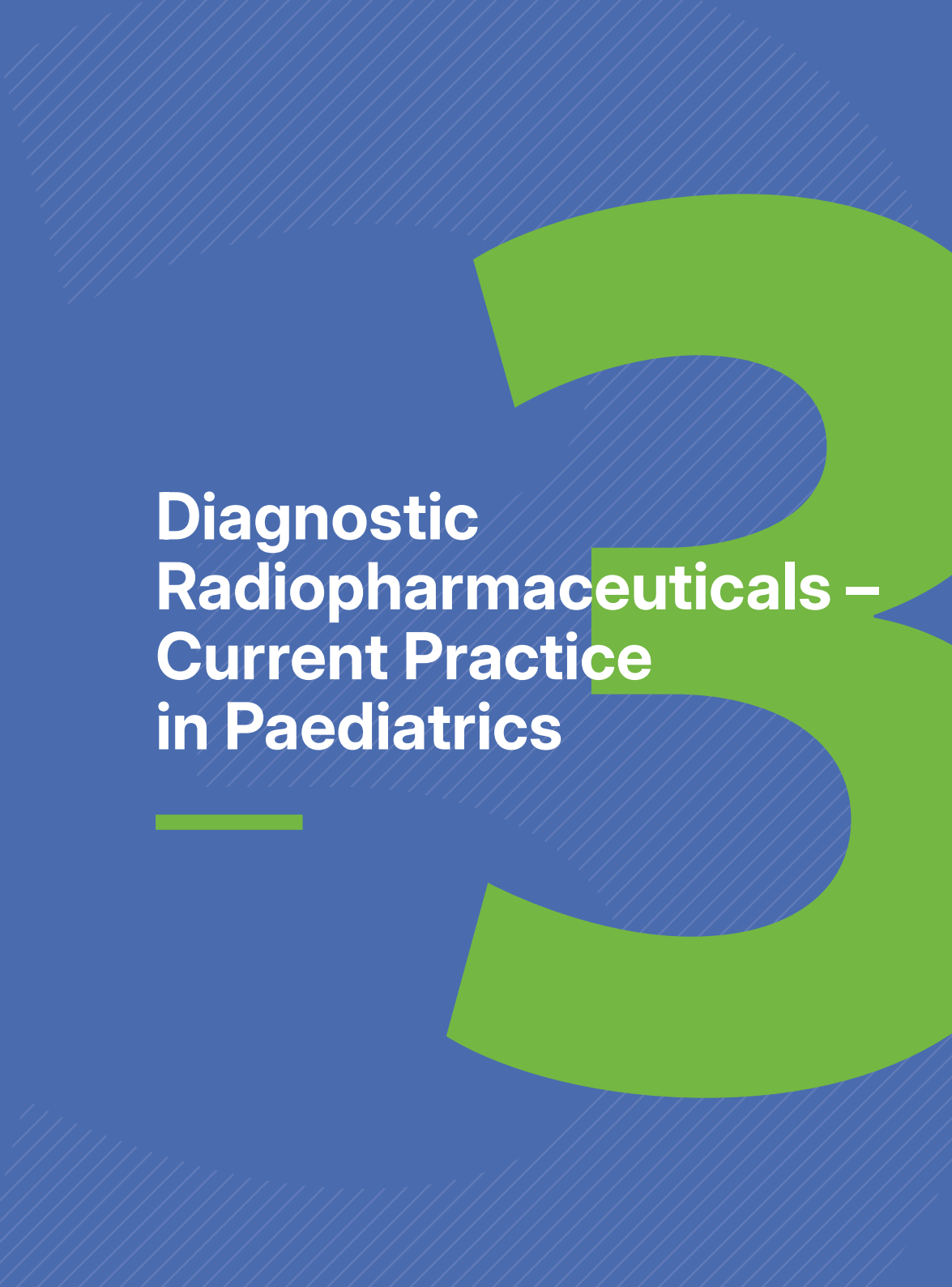
RADIATION RISK ASSESSMENTS

As every patient is different, departmental radiation risk assessments are typically based on averages, assumptions, and reference data. A risk assessment performed with adults in mind should not be used for paediatric patients without a review of these underlying factors. Some of these have been discussed in this chapter; however, any and all assumptions should be reviewed to ensure they are applicable to paediatric patients. These might include assumptions about radiopharmaceutical retention, relationships between administered activity and patient external dose rate, and excretion patterns. Alternative data sources may need to be found to ensure any effective dose estimates and mitigation measures are appropriate for paediatrics.

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Diagnostic Radiopharmaceuticals – Current Practice in Paediatrics

3.1

Conventional Nuclear Medicine Paediatric

Brain Perfusion SPECT in Focal Epilepsy

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EXECUTIVE SUMMARY

Brain perfusion SPECT is an established nuclear medicine neuroimaging technique that provides an assessment of regional blood flow using radiopharmaceuticals labelled with technetium-99 metastable (^{99m}Tc). It is a technique that has significant value in resistant epilepsy, as it can contribute to identifying epileptogenic foci.

The success of these studies, particularly in a paediatric setting, is rooted in patient preparation and harmonisation of the acquisition and reconstruction parameters. When it comes to patient preparation, having an open conversation with both the patient and their caregivers and maintaining a calm environment with dimmed lights and minimal sensory stimuli is paramount. Moreover, use of standardised acquisition and reconstruction parameters is essential to ensure diagnostic reliability and should be given particular consideration when making comparisons between ictal and interictal scans or against a database of healthy individuals.

Conducting brain perfusion SPECT in focal epilepsy requires collaboration among various stakeholders, namely personnel from the Nuclear Medicine department (radiographers/technologists, clinicians, physicists, and nurses) and personnel from the hospital's epilepsy and telemetry teams. Cross-team training should be provided, and effective communication should always be maintained to optimise care of paediatric patients and ensure their safety.

Keywords: Brain perfusion; SPECT; Paediatrics; Epilepsy; Neuroimaging

INTRODUCTION (HISTORY AND PRINCIPLE)

The concept of tomographic imaging was introduced in the 1960s/70s. Understandably, in those days, the tomography acquisition was performed using single photon emission tomography (SPET) rather than single photon emission computed tomography (SPECT), due to the reconstruction process using optical rather than computerised methods [1]. In early tomographic imaging, the acquisition method deployed was to manually rotate the patient in front of a static camera.

Although SPECT is currently used to acquire images of a variety of anatomical areas and for different conditions (referred to as whole-body SPECT), the first clinical SPECT systems were specifically designed to image the brain [1]. Dedicated systems such as SPRINT and SPRINT II were single photon ring tomographs, whereas Headtome was the first emission tomography system capable of acquiring SPECT and positron emission tomography (PET) data [2–4]. The single-slice detection efficiency of the SPRINT camera, in which the patient's head was required to pivot on the horizontal axis, thereby providing images at different angulations, was superior to that of the rotating Anger camera.

Nowadays, classical Anger cameras, hybrid Anger cameras with computed tomography (CT) and cameras with cadmium-zinc-telluride (CZT) detectors are all used in brain perfusion studies. Particularly with the latter, the CZT detectors allow improved temporal resolution and enhanced sensitivity, which translates into brain perfusion studies with higher diagnostic quality [5, 6].

Concurrently with the software and hardware development, in 1985, a team of scientists in Amersham, United Kingdom (UK) developed the first radiopharmaceutical capable of crossing the blood-brain barrier and imaging the cerebral blood flow [7]. Hexamethylpropylenamine oxime labelled with technetium-99 metastable, more commonly known as [^{99m}Tc]Tc-HMPAO, was introduced in studies of patients presenting with focal epilepsy, aiding reporting on the perfusion patterns in the ictal, postictal and interictal phases [8].

Overall, it was noted that any radiopharmaceuticals with the potential to be used for brain perfusion SPECT studies needed to possess three distinct characteristics [9]:

1. The radiopharmaceutical must cross the blood-brain barrier (BBB).
2. The tracer's initial distribution must be proportional to the regional cerebral blood flow (rCBF).
3. During the first-pass extraction across the BBB, the tracer must be retained for a sufficient amount of time to allow imaging to be performed.

CLINICAL INDICATIONS AND CONTRAINDICATIONS

Epilepsy is a chronic disease of the brain that affects between 0.5% to 1% of children, with epileptic syndromes being classified, as per the mode of onset, as focal, generalised, combined focal and generalised, or unknown [10, 11]. Of these, focal epilepsy is the most common form, with approximately 61% of cases presenting this mode of onset [12].

Clinical indications

Whilst some patients respond to pharmacotherapy with anti-seizure medication, approximately 20% of children and adolescents do not, and most of the non-respondents present with focal epilepsy. In these cases of drug-resistant focal epilepsy, surgical resection of the epileptogenic zone has proven to be a potentially suitable treatment [8].

Whilst the clinical indication for brain perfusion SPECT is to investigate focal epilepsy, its value extends beyond initial diagnosis and encompasses key aspects of pre-surgical evaluation and post-operative assessment [10, 13]:

» **Pre-surgical management of epileptic patients:** Investigation of non-lesional versus lesional epilepsy.

» **Pre-surgical lateralisation and localisation of epileptogenic foci:** To allow for the localisation of the seizure onset and enable a tailored resection.

» **Investigation of lesional epilepsy in patients experiencing post-surgical seizure:** Lesional epilepsy is a type of focal epilepsy that develops in the presence of a structural brain lesion. In certain cases, seizures may continue to develop after the removal of the epileptogenic lesion (i.e. tumour, infection sites, vascular origin, malformation), and their cause must be identified in order to tailor the appropriate course of treatment.

Relative contraindications

Whilst some of the contraindications mentioned below are not applicable to infants and children, it is important to consider them when treating young adults.

The relative contraindications to undergoing a brain perfusion SPECT include [10, 13, 14]:

- » **Imaging of potentially pregnant adolescents:** Whilst administration of radiopharmaceuticals should be avoided during pregnancy, a risk-benefit analysis should be conducted on a case-by-case basis. Where possible, the brain perfusion scan should be delayed until after the pregnancy.
- » **Breastfeeding patients:** A 4h pause in breastfeeding and discarding of expressed feeds is often recommended in the summary of product characteristics for some radiopharmaceuticals.
- » **Imaging patients under sedation or anaesthesia:** General anaesthesia can impact on brain perfusion, particularly when it is administered less than 30 min after administration of the radiopharmaceutical. However, in cases of non-cooperation or inability to cooperate, sedation or anaesthesia can be considered.

Considerations

Communication is key in nuclear medicine, and it is even more important when imaging paediatric patients, as it is vital to communicate with the patients and their parents or carers [10, 15]. Guardian consent and patient assent should, therefore, be considered. When performing neuroimaging studies in the paediatric population, it is important to state that:

- » **Parents need to be instructed to notify the medical team when ictal signs start to occur:** If the radiopharmaceutical is administered immediately after the seizure activity has terminated, the regional cerebral blood flow will not reflect the true acute

ictal occurrence but will rather represent a diffuse brain activation pattern. Hence, the radiopharmaceutical will need to be administered as soon as the first ictal signs are noted/during the seizure to enable an appropriate representation of the affected regional cerebral blood flow.

- » **Intradepartmental care and training:** When conducting perfusion brain studies, it is essential that there is continuous monitoring of the epilepsy patients. Specifically, for interictal studies, it is important that the Nuclear Medicine teams are aware of potential ictal signs that can occur during the radiopharmaceutical uptake and/or image acquisition phases. Not only should anti-seizure medication be available in the uptake bays or scanning rooms, but any occurrences also need to be appropriately documented so they can aid in reporting the images. Conversely, during ictal studies, the radiopharmaceutical is administered in an environment outside the Nuclear Medicine department. It is therefore important that the telemetry and/or nursing team is trained in radiation protection principles and safety.

PATIENT PREPARATION AND AFTERCARE

Patient preparation

If a patient is on any type of medication that might affect cerebral flow or have the potential to influence radiopharmaceutical uptake, it is important that this is discussed with the nuclear medicine physician and the referring doctor.

General advice is that for both phases of this study (ictal and interictal), cerebral stimulants (including pharmaceutical drugs, caffeine and nicotine) and any drugs

that might affect cerebrovascular blood flow (such as acetazolamide) should be withdrawn for 72h. If the patient is on anti-epileptic medications, please note when the last dose was taken. Any modification to anti-epileptic therapy should be based on a clinical decision made by the treating neurologist/epileptologist, rather than on a procedural requirement. Oral and IV radiological contrast media should also be avoided 24h prior to scanning.

a) Ictal phase

- i. The patient should be kept in a calm environment with dimmed lighting.
- ii. The telemetry/nursing team will ensure the patient is connected to an electroencephalogram (EEG) for seizure monitoring.
- iii. The patient should have an IV cannula in situ, and patency should be checked by performing a saline flush prior to injection and connection to the infusion set.
- iv. The injection will be given as a bolus upon identification of a seizure by EEG.
- v. As soon as the injection is done, the nuclear medicine technologist team should be informed.
- vi. It is important that the time of injection is recorded promptly and made available to the nuclear medicine team.
- vii. The patient should always be accompanied by a nurse and/or telemetry team, whether the procedure takes place on a ward or in the Nuclear Medicine department.

b) Interictal phase

- i. The patient will require an IV cannula in situ.
- ii. Continuous EEG monitoring should be performed to ensure that the patient is

seizure-free during injection. However, if EEG monitoring is not possible, the patient must be deemed clinically seizure-free for 2 hours prior to injection.

- iii. If clinically possible, high-quality interictal SPECT imaging should be performed in epilepsy patients at least 24h after focal aware seizures and 48h after focal impaired awareness and focal-to-bilateral tonic-clonic seizures.

iv. Before injection, the patient should be kept in a quiet room with dimmed lights for 10–20 minutes. Carers/parents should be asked to keep movement and noise to a minimum.

v. After the injection, the above room conditions should be kept for a further 30 minutes before the scan takes place.

Aftercare

There are no known side effects from ictal or interictal scans. However, the following standard radiation protection precautions should be adopted after the examination:

- » Carers/parents should wash their hands thoroughly after a nappy change, or the child should be encouraged to wash their hands after using the toilet.
- » Avoid close contact with pregnant staff members and/or pregnant mothers.
- » Do not bath small children for 24h, due to the risk of urinating in the water.
- » In the event that your patient is an inpatient/ward patient, radiation protection instructions should be given to the team looking after the patient. These can be given in paper form and/or electronically.

RADIOPHARMACEUTICAL

In Europe, two radiopharmaceuticals have been noted for their use in brain perfusion SPECT studies: [^{99m}Tc]Tc-HMPAO and [^{99m}Tc]Tc-ECD. Both tracers are lipophilic in nature, which allows them to cross the BBB: whilst the primary complex of [^{99m}Tc]Tc-HMPAO is lipophilic and of low molecular weight, allowing it to readily cross the BBB, the [^{99m}Tc]Tc-ECD crosses the BBB by passive diffusion. Once inside brain cells, the tracers convert into less lipophilic or more hydrophilic compounds, which are unable to cross the BBB and therefore remain inside the brain cells [13][16].

The first-pass extraction of [^{99m}Tc]Tc-HMPAO is approximately 80%, and within one minute of the administration taking place, 3.5–7.0% of the administered activity can be found in the brain. Similarly, the first-pass extraction of [^{99m}Tc]Tc-ECD is between 60–70% [17].

Whilst [^{99m}Tc]Tc-HMPAO is often noted as the preferred radiopharmaceutical due to the characteristics mentioned above, its shelf life is only 30 minutes, which restricts its clinical availability. This instability stems from the stannous chloride in the HMPAO kit, which serves as a reducing agent to label the technetium. Excess stannous ions can, however, promote the decomposition of the labelled complex ([^{99m}Tc]Tc-HMPAO), giving it a short shelf-life. One mitigative action that can be taken is to add cobalt chloride or a methylene blue/phosphate buffer after reconstituting the HMPAO kit. In this manner, the stannous chloride will continue to act as a reducing agent to label the technetium, and the stabilising agents will oxidise the excess stannous ions [18, 19]. This approach allows [^{99m}Tc]Tc-HMPAO to be used for up to 4 hours after the kit has been reconstituted. Imaging should

take place between 30 to 90 min after the radiopharmaceutical has been administered [20].

The [^{99m}Tc]Tc-ECD radiopharmaceutical does not require the addition of a stabilising agent, as its shelf-life is 6h. Imaging should take place between 30 to 60 min after the radiopharmaceutical has been administered [20].

ACTIVITY AND VOLUME ADMINISTERED

Administration of radiopharmaceuticals for brain perfusion scans in infants, children and young adults must be done in accordance with the recommendations of the European Association of Nuclear Medicine (EANM) Paediatric Dosage Card (version 5.7.2016) [21].

Caution should be exercised to avoid exceeding national diagnostic reference levels.

There are no restrictions on the administered volume; however, it is advisable to dilute the drawn-up volume in saline to make a total injection volume of at least 1 mL. This is to facilitate the bolus injection.

INJECTION TECHNIQUE

The administration of the radiopharmaceutical should be performed as a bolus injection via an intravenous line in situ; this will minimise the risk of extravasation and maximise the amount of radiopharmaceutical administered.

Where possible, patients should already arrive in the Nuclear Medicine department with the cannula in place – a prior appointment with the paediatric cannulation team may be required.

Regardless of the phase in which the study is being conducted, the prepared radioactive syringe should be correctly labelled with the activity, the time of calibration, and the name of the radiopharmaceutical. Best practice also advises that two nuclear medicine technologists are involved in this process: one responsible for the draw-up and preparation of the radiopharmaceutical, and one to double-check the dispensed activity and confirm that the calibrator is set to the correct radionuclide.

a) Ictal phase

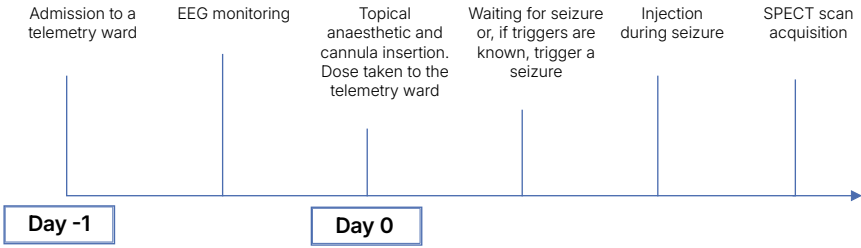
An infusion set can be set up within the ward where the patient is being monitored. Alternatively, an automatic injector can also be used for administration during the ictal phase, to ensure prompt radiopharmaceutical injection within 20 seconds of seizure onset.

The syringe containing the radiopharmaceutical should be stored in the room where the patient is being monitored, as this will ensure the quickest possible injection at the first ictal signs. Note that radiation protection regulations need to be followed to ensure safe storage and handling of radioactive substances.

Best practice recommends that a saline drip is connected to the patient (Figure 1). This will ensure the patency of the administration line prior to the radiopharmaceutical injection as well as assisting with flushing out any residual radiopharmaceutical which may be present in the line after the injection has taken place.

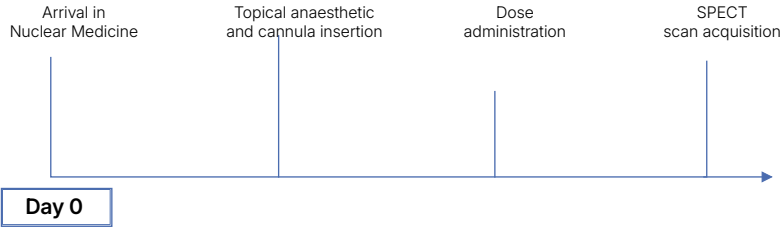


Figure 1. Display of the setup used for administering the radiopharmaceutical at the first ictal signs. Note the saline drip that allows to ensure the patency of the line as well as assisting with the flushing after the radiopharmaceutical injection. The lead container holds the syringe with the radiopharmaceutical. The plunger will be pushed, in the first instance, to push the radiopharmaceutical injection. It will then be pulled, so as to draw the saline and remove any residuals. Courtesy of King's College Hospital, London (UK)..



b) Interictal phase

For studies conducted during this phase, the same approach can be adopted as that used for injecting and scanning of outpatients.



IMAGING PROTOCOL AND IMAGING PROCESSING Acquisition Parameters

It is imperative that the patient's head remains still during image acquisition. To achieve this, the patient should be positioned supine, with their head in the camera's head-holder support and lightly restrained to minimise involuntary movement during acquisition. If the patient's head is too small for the holder, foam can be placed on both sides of the head to ensure no tilt or angulation. Moreover, the patient should be positioned for maximum comfort and stability. For children and young adults, this can be attained by placing a pillow under

the patient's knees, as this technique will reduce the pressure on the lower back. For infants, vacuum mattresses or sandbags can be used to stabilise the paediatric patient and reduce movement. Additionally, any electrodes on the back of the patient's head should be removed prior to image acquisition. This will ensure the patient is comfortable and will foster more cooperation. The reader should refer to the 2009 EANM guideline for brain perfusion SPECT and its subsequent 2024 update for advice on standard acquisition parameters for brain imaging [10, 20]. In Table 1 we present an example of the acquisition parameters used in the Nuclear Medicine department at King's College Hospital.

Brain SPECT	*Collimator	LEHR (low energy high resolution) or Fan-Beam	
	*Energy photopeak	140 KeV, 15% width	
	Orbit	Circular	
		Mode	Step and shoot
	Number of projections	128	
	Time per projection	40s or 26s (paed)	
	*Rotation	360	
	*Starting position	0	
	*Matrix	128×128	
	Zoom	1.00 (no zoom)	
	*Table height	Isocentre	
	Radius of rotation	As close as possible (ideally <15cm)*	

Table 1. Acquisition parameters for paediatric brain perfusion SPECT studies used at King's College Hospital.

Note that the radius of rotation should be the same for both ictal and interictal SPECT – an appropriate record of the radius of rotation is very important to ensure consistency and comparability between phases.

All parameters marked (*) should be considered standard; the remainder may be adapted per the department's protocol.

Reconstructions and Processing Parameters

After image acquisition, technologists/radiographers are responsible for reviewing the acquired data in cine mode to check for any movement.

Post-processing and reconstruction of brain perfusion imaging can also be undertaken by a technologist/radiographer

in conjunction with the radiologist/nuclear medicine physician.

The reader should again refer to the 2009 EANM guideline for brain perfusion SPECT and its subsequent 2024 update for guidance on reconstruction and processing parameters [10, 20]. In Table 2 we present an example of the reconstruction parameters used in the Nuclear Medicine department at King's College Hospital.

Ictal and interictal images may be analysed visually and, when available, with regions of interest (ROI)-based or with voxel of interest (VOI)-based methods, including ictal–interictal subtraction and comparison with normative databases where appropriate. Several software programs are available for the visual and quantitative analysis of perfusion SPECT [23, 24].

Brain SPECT	Type of Reconstruction	Corrections			Post reconstruction (regardless of reconstruction)
	Filtered Back Projection (FBP)	Scatter	Attenuation: Chang Method or Computed Tomography (CT) Attenuation Correction (AC)	Resolution recovery	Butterworth filter: cut-off 1.4, order 5
	Ordered Subset Expectation Maximisation OSEM: 5 iterations and 16 subsets				Gauss filter: cut-off 0.90

Table 2. Reconstruction parameters for paediatric brain perfusion SPECT studies used at King's College Hospital.

IMAGE INTERPRETATION

It is worth noting that there are two visually distinct patterns of cerebral perfusion on brain perfusion SPECT scans. If the scan is performed during the ictal phase, then increased perfusion will be noted in the brain regions involved in seizure generation and early propagation. If the scan is performed during the interictal phase, the networks within the epileptogenic zone will appear hypoperfused [8].

Below are images obtained from interictal (Figure 2) and ictal (Figure 3) studies performed on an 18-year-old patient with frequent frontal seizures. A previous MRI scan had been noted as "normal", and an EEG suggested activity in the right supplementary motor area (SMA). The interictal and ictal studies were performed to guide the epilepsy surgery.

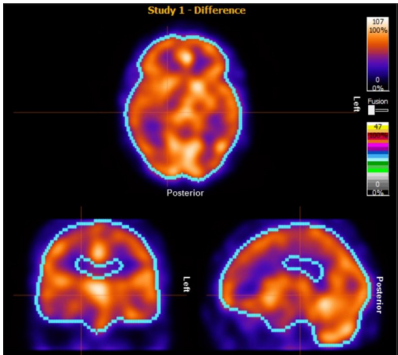


Figure 2. Interictal SPECT study. Courtesy of King's College Hospital, London (UK). A hypoperfused area was noted on the right anterior lobe, identified by the yellow arrow.

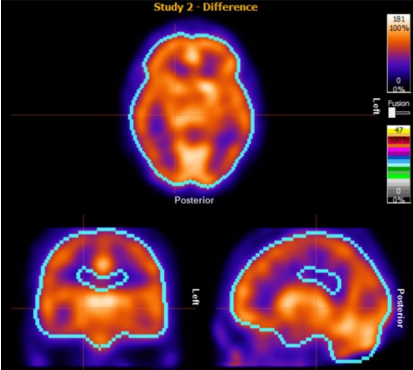


Figure 3. Ictal SPECT study. Courtesy of King's College Hospital, London (UK). Increased perfusion can be seen in the right medial temporal lobe, identified by the white arrows.

The ictal study was then subtracted from the interictal study, with Figure 4 indicating the differences in cerebral perfusion.

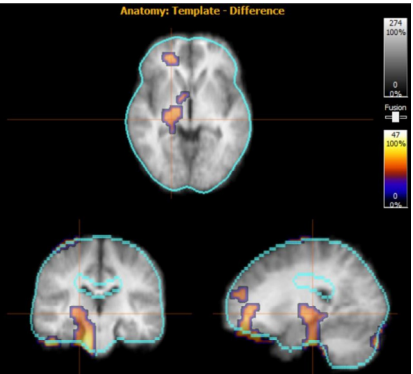


Figure 4. Study 2 - Study 1. Courtesy of King's College Hospital, London (UK). The subtraction image reveals differences in perfusion in the right medial temporal lobe as well as the right anterior hemisphere.

The results demonstrate a 19% difference in the right medial temporal lobe and a second right anterior subcortical defect.

PATIENT PATHWAY (EXAMPLES OF CLINICAL CASES)

Primarily, coordination between the Telemetry and Nuclear Medicine departments is essential to organise available dates, taking into account available staff and facilities.

Coordination with your central or local radiopharmacy is imperative. When using the first, it is important to ensure that radiopharmaceutical supply is available during the potential 3 days of the ictal/interictal study, and that the calibration times align with those of the department; when using the latter, it is paramount to ensure that cold kits are available and that the Mo-99/Tc-99m generator contains sufficient activity to reconstitute the cold kits.

Impact on daily clinical schedule

i. **Camera schedule:** As this study comprises two different phases — ictal and interictal — the departmental diary slots will need to be reserved for the duration of the entire study. As an example, if the interictal scan is scheduled for Monday morning, the ictal study should be planned for the two following days (Wednesday and Thursday). On the day of the ictal phase, morning and afternoon slots must be reserved, as the patient's presentation with ictal signs is unpredictable.

ii. **Available facilities:** If the ictal phase does not occur in a patient ward/epilepsy ward/telemetry unit, patients will need to be transported to the Nuclear Medicine department via bed, accompanied by the epilepsy and telemetry team, and monitored by EEG. In these cases, it is essential that a room is available within the Nuclear Medicine department for the entire day, to

accommodate this patient. This room should ideally provide a quiet/isolated environment, as the patient should not be exposed to outside stimuli for a few minutes prior to, during and following the injection, as this will impact on brain activity and cerebral blood flow.

Staff — Trained nuclear medicine technologists/radiographers should be available to perform scanning. Other personnel including nuclear medicine nurses, members of the physics team and telemetry staff should also be present depending on your departmental organisation and Standard Operating Procedures (SOPs).

Nocturnal studies

Whilst nocturnal studies can be performed, it is important to note that only the [^{99m}Tc]Tc-ECD radiopharmaceutical is suitable for conducting these. Often, the radiopharmaceutical is administered overnight, with imaging potentially taking place first thing the following day (or even overnight if the Nuclear Medicine department has a night shift). In this regard, when planning nocturnal studies, it is important to ensure that the radiopharmacy can supply [^{99m}Tc]Tc-ECD rather than [^{99m}Tc]Tc-HMPAO on the required date and time.

CONCLUSION

Brain perfusion studies are of the utmost importance in the clinical management of paediatric patients with epilepsy. Whilst clinical protocols/departmental SOPs may vary from department to department, the basics of performing ictal and interictal studies are the same.

Continuous supervision of epilepsy patients is required, regardless of the phase of the study being conducted. Therefore, all healthcare professionals involved in patient care must be trained to recognise ictal signs and understand the appropriate actions to take.

Despite their importance, SPECT perfusion studies are impacted by the gamma camera's low spatial resolution, particularly in comparison with PET scanners. The limited spatial resolution combined with the potential for partial volume effects may hinder the visualisation of small lesions which, in the context of epilepsy, are extremely important to detect. In addition to this, the long acquisition time, resulting from using only 2–3 detectors to acquire an orbit of 360°, may lead to movement artefacts. This is particularly important when considering the paediatric population, who may be less cooperative than adults.

Cameras with CZT detectors may be a suitable solution for increasing spatial resolution and reducing the acquisition time in brain SPECT studies; however, many departments only have access to conventional or hybrid gamma cameras. One further advantage of this new technology is its ability to simultaneously acquire and distinguish different isotopes. Although the most common radiopharmaceuticals for performing SPECT brain perfusion studies are [^{99m}Tc]Tc-HMPAO and [^{99m}Tc]Tc-ECD, others such as Xenon-133 and [¹²³I]I-IMP are also available and studies comparing the distribution patterns between different radiopharmaceuticals have been conducted [25, 26].

Future clinical work may also rely on radiomics and machine learning models in

the localisation of epileptogenic zones, as quantitative data extracted from ictal and interictal scans has the potential to be used to train models to identify subtle perfusion differences.

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Thyroid Scintigraphy

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EXECUTIVE SUMMARY

Thyroid scintigraphy is an available diagnostic tool for the paediatric population for benign thyroid conditions such as congenital hypothyroidism (a disorder present at birth in which the baby's thyroid is unable to produce enough thyroid hormone), diffuse thyroid enlargement and assessment of thyroid nodules [1]. Congenital hypothyroidism is the most treatable cause of intellectual impairment, and its diagnosis is time critical [2]. Often used as an adjuvant tool along with ultrasound (US), the thyroid scintigraphy findings assist in differentiating between thyroid dysgenesis (abnormal development of the thyroid gland, including atypical location), ectopic thyroid (abnormally located thyroid gland outside its normal pre-tracheal position), and to predict the necessity for long-term thyroid hormone replacement therapy [3]. In view of these indications, the scheduling of the scan for this clinical indication ought to be prioritised.

[^{99m}Tc]Tc-pertechnetate, which is readily available and has a short half-life of 6 hours, is the standard radiopharmaceutical of choice for the scintigraphic assessment of thyroid conditions in children of all ages, following radiotracer activity adjustment based on weight, and increased hydration post-procedure in order to promote renal excretion of the radiotracer [4].

The management of the paediatric patient requires not only knowledge of medical, clinical and technical aspects, but also a caring attitude to support the parents or caregivers of the child, managing their expectations and providing clear guidance and instructions. This will help to build confidence and trust while increasing compliance with the procedure and the post-scan radiation protection advice.

This chapter intends to reflect best practice, through reference to official guidelines as well as the authors' practical experience.

Keywords: Thyroid; Endocrine; Paediatrics; Congenital Hypothyroidism

INTRODUCTION (HISTORY AND PRINCIPLE)

Paediatric thyroid disorders represent a diverse range of conditions that pose considerable challenges within the field of paediatric endocrinology.

Among the benign conditions, there is congenital hypothyroidism (when a baby's thyroid gland is not producing enough thyroid hormone) which in the United Kingdom is reported to occur with an incidence of approximately 1 in every 2,000 to 4,000 live births, exhibiting a higher prevalence in females, who are affected twice as frequently as males [5].

In these cases, timely diagnosis and intervention are crucial for mitigating physical, cognitive, and psychosocial sequelae, such as growth impairment, cognitive deficits, and behavioural changes [6,7]. For this reason, many countries routinely apply a heel-prick blood screening test at the time of birth [2].

Among the malignant conditions, the incidence of paediatric thyroid cancer remains relatively low, although differentiating thyroid cancer still represents the most common endocrine malignancy in this patient group [8]. Recent studies indicate an upward trend in this diagnosis, suggesting that despite the overall low prevalence, the rate of occurrence is increasing [9,10,11].

Coverage of the malignant thyroid conditions is outside the remit of this

chapter, which will instead focus on the purpose and practical use of thyroid scintigraphy in the benign context.

THYROID HORMONES AND FUNCTION TESTS

Thyroid function can be assessed in a relatively simple and accessible manner through a blood test. The most frequently performed thyroid blood tests are thyroid stimulating hormone (TSH), free thyroxine (FT4), and free tri-iodothyronine (FT3), which are used to ascertain if there is thyroid dysfunction or to monitor the response to therapy [2].

A brief description of each of these hormones is presented below [12]:

TSH: produced by the pituitary gland and released into the bloodstream. The thyroid reads the level of TSH in the blood and detects if it needs to produce more thyroid hormones. For instance, if there is too much TSH in the blood already, then a normally functioning thyroid knows that it does not need to increase production of the T4 and T3 hormones. Similarly, if there is already too much T4 and T3 in the blood, the pituitary gland detects this and knows that it does not need to increase TSH production.

T4: produced by the thyroid as a result of regulation by the pituitary gland and hypothalamus. It is the most abundant thyroid hormone circulating in the blood, and can convert into a more active form (T3).

T3: 20% produced directly by the thyroid, 80% produced via T4 conversion. It is the active form that directly affects the other organs.

On a normal basis, these hormones are kept in a relative balance, regulating each other. They influence weight and determine

energy levels, internal temperature, skin, brain function, muscle control, and hair and nail growth, among others. All of these can impact a child's growth, hence the great importance of identifying any thyroid disorders early [13].

CLINICAL INDICATIONS AND CONTRAINDICATIONS

Thyroid scintigraphy is usually performed in paediatric cases for the following clinical indications: congenital hypothyroidism, diffuse thyroid enlargement and presence of thyroid nodules [14].

Congenital hypothyroidism

This term pertains to when the child is born with an insufficient amount of thyroid hormone. This condition can be either temporary or permanent [15].

Temporary causes relate to the pregnancy and may include [15]:

- » Maternal antibodies that block thyroid function
- » Maternal medication for thyroid conditions
- » Iodine deficiency in the mother's diet
- » Excess iodine in the mother's diet
- » Exposure to iodine-containing antiseptics used in maternal or newborn surgical procedures (e.g. C-section) or contrast media in radiological procedures [16].

In these cases, imaging is typically unnecessary because the cause is usually quickly identified and consequently resolves on its own, with normal endogenous production of thyroid hormone resuming within the first postnatal months [17,18].

Permanent congenital hypothyroidism can arise from several conditions, such as [18]:

» Primary congenital hypothyroidism [19]:

- Thyroid dysgenesis, referring to problems with the development of the thyroid gland. This can be classified in 4 types:
 - Agenesis: the complete absence of the thyroid gland
 - Hemiagenesis: the absence of part of the thyroid gland
 - Hypoplasia: underdevelopment of the thyroid gland
 - Ectopia: the thyroid tissue is in an unusual location (e.g. below the tongue).
- Dyshormonogenesis: referring to a genetic disorder that causes an inability to produce thyroid hormones.

» Central congenital hypothyroidism is related to hypopituitarism [20]. This relates to the malfunctioning of the pituitary gland and may be associated with a condition called “multiple pituitary hormone deficiencies”. When this happens at birth, it is also known as ‘congenital hypopituitarism’ and is potentially life-threatening on account of the possible co-occurrence of adrenocorticotropin hormone and growth hormone deficiency, which can result in severe hypoglycaemia and adrenal crisis [21].

These conditions often require treatment to ensure that the baby receives enough thyroid hormone for proper growth and development [22].

Thyroid enlargement, Thyrotoxicosis and Thyroid Nodules

Thyroid enlargement is predominantly observed in female teenagers, and is linked to Hashimoto’s disease, nodular hyperplasia, Graves’ disease, or thyroid carcinoma [12].

Thyrotoxicosis results from excess thyroid hormones in the bloodstream, causing an overactive thyroid (hyperthyroidism). Symptoms include weight loss, intolerance to higher temperatures, anxiety, palpitations, and tremors. Graves’ disease is the main cause of hyperthyroidism in children [23].

Thyroid nodules are more common in adults than in children, though in the paediatric cohort they carry a higher likelihood of being malignant [12].

Following the most recent guideline from the European Thyroid Association, imaging is not automatically considered for the diagnostic workup of paediatric cases of Graves’ disease. Nevertheless, in the absence of signs of thyroid autoimmunity, thyroid ultrasonography and thyroid scintigraphy are advised. When comparing these two options, thyroid ultrasonography with Doppler blood flow assessment is presented as the preferred option in an attempt to minimise unnecessary radiation exposure in paediatric patients, while the thyroid scintigraphy examination is better suited for assessing high activity (“hot”) autonomous nodules and for excluding low iodine uptake thyrotoxicosis [23][24].

There are usually no absolute contraindications for thyroid scintigraphy, although caution should be exercised with teenage patients who may be of fertile age, where pregnancy must be excluded as part of clinical procedures and protocols [25].

Patient Preparation and Aftercare

Communication with the patient’s parents is essential regarding preparations to be followed prior to the examination, as well as information on what to expect on the day of the procedure. Local leaflets and videos can assist significantly in preparing both the child and their parents for this procedure.

Pre-procedure medication checks

Upon referral of the patient, a full list of the patient’s medications should be recorded. According to EANM guidelines [1], specific recommendations include discontinuing iodine substances such as amiodarone for 3–6 months, while kelp intake should cease for 4 weeks. Imaging with iodine contrast agents and iodine-containing medications, antiseptics, and solutions should be paused for 4–6 weeks. Checklists of required assessments or pre-checks can be useful, but the technologists must apply clinical judgement and ensure questions are appropriate and clinically relevant (e.g. not asking the parents of a newborn whether they have taken amiodarone in the past six months).

In the case of thyroid medications such as levothyroxine (LT4), it is recommended that it should be paused for 4 weeks, whereas liothyronine (LT3) should be halted for 2 weeks. Carbimazole can be discontinued 3–7 days prior to the procedure [1].

In neonatal cases, there are considerations regarding the cessation of thyroxine. By taking immediate action, the procedure can even occur prior to any thyroid medication being commenced. This highlights the importance of clear, streamlined protocols. Some departments recommend stopping the medication for

24 hours to allow visualisation of existing thyroid tissue. However, due to the risks associated with delaying the initiation of treatment [26], guidelines indicate that discontinuation is unnecessary within the first 5 days of treatment.

It is important to note that in cases where the medication needs to be stopped, the referring consultant, usually a neonatal endocrinologist, must be informed in order to ensure that it is safe to interrupt the medication of the patient for the required amount of time.

After the procedure, parents and nursing staff must be reminded to restart the prescribed medication as usual.

Departmental considerations

In most hospital settings, cannulation procedures occur within the paediatric ward; thus, effective coordination with the paediatric team is essential for a smooth transition on the day of the procedure.

Ahead of the patient arriving, the scanner room should be set up to create a calming environment for the child. For babies and newborns, this can be achieved by using soft ambient lighting to reduce anxiety and sufficiently warm room temperature. For older children, this can be achieved by setting up colourful and inviting decor (e.g. music, posters on the walls, stickers). Any immobilisation devices should be ready to use, and the staff must know how to use them properly.

As part of the informed consent, post-procedure radiation protection measures should be given to parents; this includes explicit guidelines on safely managing nappy changes and the need for frequent handwashing while doing so, as well as the need to increase the baby’s hydration and for the patient to maintain a safe distance

from other children (e.g. siblings or fellow pupils at school) for at least 6 hours. In the case of older children, they should ensure that they flush the toilet twice after urinating, practice good hand hygiene, and be mindful of urine spills.

For inpatient paediatric patients returning to the ward, radiation protection measures should be given to nursing staff. Distance should be maintained between the patient and other paediatric patients.

It is advisable to have a simple card or letter with these instructions, that can be given to the parents or guardians, or to the nursing staff.

Radiopharmaceutical

The preferred radiopharmaceutical is ^{99m}Tc -pertechnetate. This radiopharmaceutical mimics the iodine metabolism and enters the thyroid cells by the sodium-iodine symporter, a transmembrane protein located on the basolateral membrane of these cells. However, it is not organified, therefore it washes out of the thyroid cells within 30 min, so it is important to scan between 15–20 min post injection [1].

Additionally, ^{123}I -Nal can also be used, particularly in the context of suspected thyroid cancer evaluation [1]. Given the focus of this chapter on benign conditions, the application of ^{123}I -Nal should not be considered.

It is worth noting though that, in theory, ^{123}I -Nal is the most physiological radiopharmaceutical and yields better images than Tc-^{99m} sodium pertechnetate, even with low uptake [16]. Nonetheless, while ^{99m}Tc -pertechnetate can be easily and quickly sourced, ^{123}I -Nal usually needs to be ordered from an external supplier, leading to possible delays in

booking the scan (if the aim is to assess congenital hypothyroidism, then it is urgent, and using ^{123}I -Nal would cause unnecessary delays). Additionally, oral administration of ^{123}I -Nal commonly requires 2 h of fasting before the scan to ensure rapid and complete absorption [16], which may not be feasible or may cause additional stress to the parents.

^{99m}Tc -pertechnetate is more commonly available, has a shorter half-life (6.04 h) and a lower cost, therefore remains the preferred radiopharmaceutical for thyroid imaging [1].

Activity and Volume Administered

The activity administered must be calculated using the most recent version of the EANM Paediatric Dosage Card (version 5.7.2016) [27]. It is essential to verify that the updated version of the dosage card is being utilised, and all dose calculations should be double-checked by another qualified technologist before injecting the patient. The minimum activity specified is 10 MBq.

The activity is determined using the following formula:

Activity Administered (MBq) = Baseline Activity x Multiple.

For example, when calculating the activity to be administered for a child weighing 10 kg, the baseline activity is 5.6 times the multiple, which in this case is 2.71 (^{99m}Tc -pertechnetate (Thyroid) is Class B"), giving 15.17 MBq.

If quantification is required, pre- and post-syringe measurements are essential. This can be done in a dose calibrator or by imaging the syringe in the camera gamma. This also ensures that activity to be administered is not below 10% of the diagnostic reference level.

Injection Technique

The child and family's experience in the department should be as straightforward and smooth as possible. It is advisable to allow a longer time slot for these patients, in case they require additional entertainment, persuasion or reassurance.

As aforementioned, departments often rely on cannulation pre-booking in paediatric wards where trained paediatricians or specialised nurses carry out the cannulation process. However, since the availability of these professionals can sometimes be limited, in departments that experience a high volume of paediatric patients, nuclear medicine technologists can receive focused training on how to perform cannulation of paediatric patients within the department.

The use of a topical anaesthetic cream, such as one containing lidocaine and prilocaine, administered approximately one hour prior to venous access, can significantly reduce the discomfort associated with needle insertion [28]. The use of direct injections or butterfly devices is discouraged, and a cannula is preferred, since it is more stable and likely to stay in-situ, leading to higher chances of successful administration.

Distraction techniques appropriate to the child's age should be applied, so ideally at least two members of staff should be present: one performing the actual cannulation procedure, and the other playfully distracting the child and immobilising their arm/hand to prevent sudden movement [29]. Venipuncture and injection pose considerable challenges in paediatric patients, thus distraction techniques [30], the implementation of incentive-based strategies (e.g. toys, bravery certificates, child-specific plasters),

and the physical comfort provided by the embrace of their parent(s) can promote cooperation during the procedure. The technologist should be able to assess the level of parental collaboration: by observing how the parents interact with the child, technologists can determine whether their involvement will help maintain calmness and tranquillity or unintentionally increase the child's distress, and adjust their approach accordingly.

Whether the patient is cannulated in the paediatric ward or in the Nuclear Medicine department, checking the cannula's patency before administering the radiopharmaceutical is of paramount importance. For this purpose it is important to flush the cannula with at least 5 mL of 0.9% sodium chloride.

After administration of the radiopharmaceutical, the cannula must be flushed again (ideally with 10 mL of saline) to avoid large residuals of radiotracer in the syringe/cannula, which would lead to an administered activity below the recommended 10% of the dose reference limit.

Imaging Protocol and Imaging Processing

Anterior and lateral views should be acquired 15 to 20 minutes after intravenous administration of the radiopharmaceutical. The lateral views tend to be especially useful for visualisation of the linguo-located ectopic thyroid. Immediately before the procedure, the child's parent is asked to give the patient a glass of water or milk to clear any mouth and oesophagus activity. This is because the radiopharmaceutical is excreted through the saliva and swallowed into the stomach, which may lead to misinterpretation of the results if it

is confused with ectopic thyroid tissue or uptake in the pyramidal lobe [16].

It is important that the child remains as still as possible during imaging acquisition, in a supine position with the neck hyperextended (a folded towel under the neck or a supplier-specific pillow may be used in toddlers and older children to adequately extend the neck). Imaging acquisition parameters are presented in Table 1 [16]. Babies may be directly positioned on the detector surface to decrease the distance between the thyroid gland and the collimator, for instance using immobilisation techniques with folded sheets, grobags, sand bags, or inflatable devices, thus improving spatial resolution

and possibly shortening the acquisition time [16]. It is really important to monitor the child for safety purposes, avoiding situations where they may roll over and fall. As stated before, it is essential to maintain a calm, friendly and composed atmosphere for the child [31] and allow enough time for the procedure to alleviate any associated stress. To allow the child to adjust to the environment, the administration of the radiopharmaceutical can be performed while the patient is positioned on the couch bed or already in the immobilisation device (if one is used). The provision of soft blankets, adjustments to the room temperature, soothing music, interactive toys, and storytelling are distracting

techniques that promote the child's comfort both before and during the procedure [32].

Cobalt-57 (57Co) pen marker should be used as an anatomical landmark. This is usually positioned in the sternal notch and mandible/chin area [16].

Image processing

In cases of congenital hypothyroidism, processing consists of displaying the static images together with the respective labelling. In cases where quantification is required, this can be performed by adding the respective pre- and post-syringe administration activity and a region of interest (ROI) following the contour for the thyroid minus the drawn background ROI adjacent to the thyroid gland. Based on this information, the processing software is capable of calculating the percentage of the injected activity that is present in the thyroid gland and the reporting physician can compare that percentage with normal reference ranges [1].

Image interpretation

On a normal scan, the two thyroid lobes would display symmetrical uptake in the basis of the neck. Faint uptake in the salivary glands and gastric mucosa is normal [1].

Abnormal results could include [1,16]:

- » absence of uptake (suggesting agenesis or transient hypothyroidism due to maternal/pregnancy factors);
- » single-side uptake (suggesting hemiagenesis);
- » focal uptake in a different location (ectopic), visualised solely or in conjunction with the thyroid gland;
- » reduced uptake (may be due to maternal antibodies, exposure to iodine, hypoplastic

gland or initiation of thyroid replacement therapy for more than 7 days) or intense uptake (suggesting dysshormonogenesis) – quantification may be helpful in these cases, using the normal reference range of 0.45–4%, or whichever the latest guidance indicates) [16].

All patterns mentioned above must be interpreted with reference to the patient's history and in conjunction with other available information (e.g. blood test results, US).

Below we present a series of examples of anonymised patient cases with differing uptake patterns, together with the respective explanations (Figures 1, 2, 3 and 4):

Parameters	Acquisition Parameters for Static Images at 15 min post-injection, using ^{99m} Tc Tc-pertechnetate
Collimator	» LEHR (LEGP is also a suitable option; a pinhole collimator would be an ideal choice, but it is becoming increasingly unavailable in Nuclear Medicine departments and would still require lateral images acquired with another collimator).
Acquisition mode	» Static Anterior, Anterior with marker and Lateral views. » Field of View (FOV): head, neck and chest. It is important to ensure that the arm/hands (where the cannula is located and likely has a small residue of activity) should be by the side and not curled, bent or cuddled into the neck/chest area. » When using a pinhole collimator, the thyroid should appear within the centre and within 2/3 of the FOV to avoid distortion of the gland anatomy [16]. » For the lateral view of the neck (indicated in cases of ectopy), the detectors may be moved to the side or it may be obtained with the infant lying on his/her side [16]. » Anterior right and left oblique (or SPECT) are not used for newborns with suspicion of congenital hypothyroidism, but may be helpful in older children when assessing other benign conditions. These would be acquired under the same conditions as the Anterior.
Pre-set parameters	» Stop time 300 sec or 100 to 200× 103 counts, whichever occurs first. » Matrix: 128×128 or 256× 256 » Pixel size: 1.77 (mm) » Patient positioning and location: Supine, Feet First » Zoom: 1.5 to 2 » Photo Peak and Energy window: 140.5 KeV +/-7.5–10 %
Quantification	If quantification is performed, pre- and post-syringe administration images are acquired (same set parameters as above). These images are obtained in posterior mode for approximately 10 seconds.

Table 1. Acquisition parameters for static thyroid scintigraphy imaging. This table is based on the EANM practice recommendations, amended where necessary to reflect local experience [1].

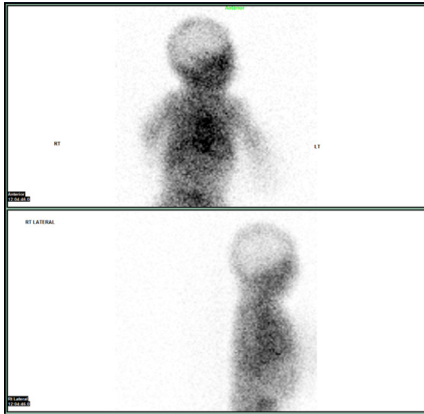


Figure 1. Clinical question in the referral: Suspected congenital hypothyroidism. Male patient, 1 month old. Anterior and lateral planar imaging was acquired and showed no evidence of visible thyroid tissue in the head/neck area. The ultrasound confirmed a normally located and normal appearing thyroid gland. Absent uptake in an anatomically normal thyroid suggests possible maternal antibody suppression or transient congenital hypothyroidism. Blood test follow-up recommended. Later it was observed that the patient had not discontinued the thyroid medication 24 hours prior, in accordance with departmental protocol. This discrepancy led the reporting physician to categorize the report as inconclusive. The featured images are reproduced courtesy of Maidstone and Tunbridge Wells NHS Trust Hospital.

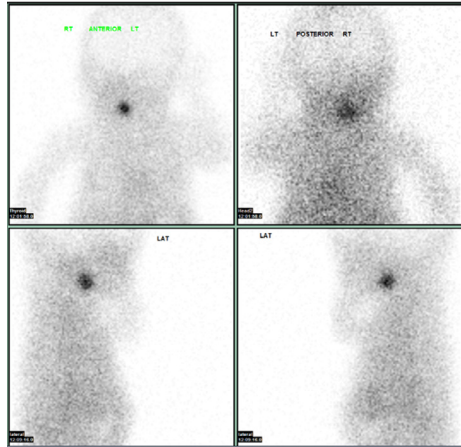


Figure 2. Clinical question in the referral: Suspicion of Congenital Hypothyroidism; TSH >100; urgent, (within 48h). Female patient, 13 days old. Anterior and Lateral planar imaging of the upper body confirms a rounded solitary focus of intense uptake located centrally in the posterior oropharyngeal region rather than in the lower neck. This raises the suspicion of a lingual thyroid rather than an orthotopic cervical thyroid. It was advised that anatomical localisation should be visible at the impending neck ultrasound, which indeed offered confirmation. In conclusion, evidence of uptake within oropharyngeal rather than cervical thyroid tissue suggested an ectopic thyroid. The US 6 days later was reported as "no convincing normal thyroid tissue identified in the neck, however there is a midline solid round echogenic mass at the base of the tongue measuring approximately 8.3 x 8.6 x 6.6 mm in diameter consistent with an ectopic lingual thyroid and which would correspond to the area of uptake seen on the nuclear medicine scan". The featured images are reproduced courtesy of Maidstone and Tunbridge Wells NHS Trust Hospital.

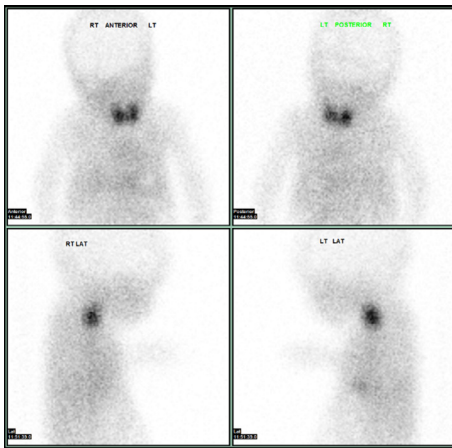


Figure 3. Clinical question in the request: Newborn screening results showed suspicion of congenital hypothyroidism. Male patient, 22 days old. Anterior and Lateral planar imaging showed increased uptake within an orthotopic thyroid gland located anteriorly in the neck. No abnormal lingual uptake was observed. In conclusion, the increased uptake confirms a normal trapping function within the orthotopic thyroid gland. This was deemed suspicious for dyshormonogenesis. The featured images are reproduced courtesy of Maidstone and Tunbridge Wells NHS Trust Hospital.

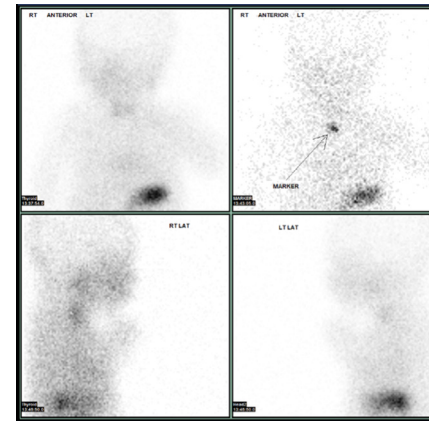


Figure 4. Clinical question in the request: Suspicion of congenital hypothyroidism. Male, 6 weeks old. Anterior and Lateral planar imaging showed very faint uptake in the normally placed small thyroid gland. Such low levels of uptake may be seen in hypoplasia or suppression by maternal antibodies. The reporting physician indicated that this was not the appearance of dyshormonogenesis or athyreosis. These appearances should be correlated with the impending thyroid ultrasound. The US was conducted 22 days later and it reported that the thyroid was easily identified and appears of normal size and echogenicity. The right lobe measures 22 mm in craniocaudal dimension by 7 x 8 mm in transverse dimension and the left lobe measures 19 mm x 7 x 6 mm. The featured images are reproduced courtesy of Maidstone and Tunbridge Wells NHS Trust Hospital.

PATIENT PATHWAY

Thyroid scintigraphy plays a crucial role in distinguishing the underlying causes of thyroid dysfunction, particularly in cases of congenital hypothyroidism. This differentiation is vital, as conditions such as agenesis and dyshormonogenesis require distinct treatment approaches. Effective and timely collaboration among departments such as Maternity, Neonatal Services, Paediatrics, and Nuclear Medicine is essential. These requests are urgent, and the paediatric team usually aims to have the procedure completed within 48 hours. It is therefore essential to establish an efficient link with the paediatric wards for scheduling details as well as cannulation. It is also important for the ward team to be aware of the overall radiation protection measures,

and to be well informed about how to keep staff and other babies and families safe. The NM technologist should be confident enough to act in a non-alarming manner while knowing how to reply when faced with radiation protection queries. The Lead Technologist is particularly well placed to be a point of contact for this procedure, liaising closely with all entities and having decision-making autonomy to refine and expedite the workflow and notify the clinicians of any updates.

If feasible, the imaging department could consider arranging a one-stop clinic where patients can undergo an ultrasound followed by scintigraphy, which would be preferable.

CONCLUSION

Timely diagnosis of hypothyroidism in newborns has a significant impact in preventing long-term growth impairment, irreversible intellectual disability, and various neuropsychological deficits. It is vital that there are appropriate protocols in place to enable a seamless diagnosis pathway. The multidisciplinary team needs to be well coordinated to ensure timely intervention, preparation and adequate support for the child and family. A streamlined route for thyroid scintigraphy requires flexibility, responsiveness and a caring attitude from the technologist team as well as prompt reporting and communication of the results from the physician and the specialist neonatal team.

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Lung Scintigraphy

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EXECUTIVE SUMMARY

Paediatric lung scintigraphy can be challenging and requires the technologist/radiographer to adapt communication techniques to ensure both patient and carers understand the procedure. The administration of [^{99m}Tc]Tc-MAA should be scaled following the EANM Paediatric Dose Card and thought should be given to ventilation agents, weighing up patient tolerance and radiation dose.

Keywords: Lung scintigraphy; Paediatric; Radiopharmaceuticals; Ventilation. Perfusion.

INTRODUCTION

Paediatric imaging can be challenging due to the child's lack of understanding, poor compliance and limited venous access. It is important that any technologist or radiographer utilises appropriate distraction techniques, robust immobilisation devices, and clear communication methods with both the patient and their parents/carers.

Nuclear medicine ventilation/perfusion (V/Q) scans allow correlation of the airflow and blood perfusion to the lungs based on the respective patterns of distribution. V/Q scans may consist solely of planar imaging or be acquired in combination with single photon emission computed tomography (SPECT), with or without computed tomography (SPECT/CT). Alternative modalities such as magnetic resonance imaging (MRI) or computed tomography pulmonary angiography (CTPA), and non-imaging tests such as D-dimer, can aid in the diagnosis of pulmonary embolism (PE) [1]. Lung aspiration scans will also be discussed in this chapter; these scans assess the level of oesophageal reflux typically resulting in patient aspiration [3].

CLINICAL INDICATIONS

Pulmonary Embolism

Pulmonary embolic disease is caused by a blood clot within the lungs; such clots can restrict blood flow to the lung/s, and if large enough or in cases of multiple clots, especially if bilateral, the disease can be fatal. PE in children is increasingly related to infection, cancer, congenital heart disease, acquired or inherited thrombophilia, and central line placements [4]. Advances in treatment mean that critically ill children are surviving longer, thus increasing the incidence of PE [5]. Classic presentation of PE in children is asymptomatic, although symptoms can include shortness of breath, chest pain, haemoptysis, cough, tachycardia and oedema [6]. However, such symptoms can also be a sign of underlying diseases such as cancer, infection or congenital heart failure.

PE is demonstrated in V/Q scans by mismatched wedge defects between the perfusion and the ventilation images. SPECT has further increased the sensitivity and specificity, aiding discovery of small emboli [7], although there has been evidence to suggest small non-specific perfusion defects can be overcalled, leading to increased false positives in SPECT-only imaging [8].

Pulmonary Hypertension

Pulmonary hypertension (PH) can present in children at any time from infancy to adulthood and is usually diagnosed late due to the non-specific symptoms [9]. PH is defined as elevated pulmonary artery pressure. Alterations in lung development can contribute to paediatric PH, which is distinct from adult presentations [10].

The World Health Organisation has classified paediatric PH into 5 groups [11]; (1) pulmonary arterial hypertension (PAH), (2) PH due to left heart disease, (3) PH due to lung disease and/or hypoxia, (4) PH due to pulmonary artery obstructions, (5) PH due to unclear/multifactorial mechanisms.

The V/Q scan allows diagnosis of chronic thromboembolic pulmonary hypertension (CTEPH) and is recommended in appropriate work-up of paediatric hypertension [12]. Presentation of CTEPH in V/Q scans is demonstrated by significant perfusion/ventilation mismatch defects, typically in one or more segments or larger [13]. CTEPH is potentially curable by pulmonary endarterectomy, which makes timely diagnosis essential.

Chronic Pulmonary Disorders

Paediatric chronic obstructive pulmonary disease (COPD) usually presents with a chronic cough with bronchiectasis [14]. Additional chronic pulmonary disorders can include bronchopulmonary dysplasia, which is seen in premature infants requiring ventilators [15] presenting with long-term asthma-like symptoms and compromised lung function. Chronic pulmonary diseases can lead to further deterioration of lung function, infections and PH [16].

COPD typically presents on V/Q scans as a reversed mismatch, where the perfusion is usually less affected than the ventilation. The degree of ventilation defects typically relates to the degree of obstruction [17]. A normal V/Q would rule out bronchopulmonary dysplasia [18], therefore may be useful in younger patients that cannot comply with lung function testing.

Pre-operative Evaluation for Surgery

Paediatric patients can undergo lung surgery for a multitude of different indications; these include severe pneumonia, lung abscess, malignant tumour, non-cystic fibrosis bronchiectasis and congenital lung malformation [19]. A SPECT-CT lung perfusion scan allows quantitative analysis to ensure pre-operative evaluation of current lung function, enabling efficient surgical planning [20]. Additionally, combining diagnostic-quality CT and functional imaging allows for one appointment, reducing the need for multiple sedations.

Pre-operative V/Q scans have demonstrated benefits prior to and post-surgery for pulmonary artery stenosis in congenital heart disease [21]. The V/Q scintigraphy provides a baseline evaluation of the perfusion abnormality, therefore allowing selection of patients who may benefit from surgical correction while assessing their response to treatment.

Unexplained Hypoxia

When oxygen supply to a portion of the lung is insufficient to maintain homeostasis, hypoxia occurs [22]. Causes of hypoxia could be a V/Q mismatch, right-to-left shunting or hypoventilation, and it can range from mild to severe, and from acute to chronic.

V/Q scintigraphy can allow the determination of V/Q mismatches. This allows assessment of areas of decreased perfusion or reduced ventilation, both of which could result in hypoxia due to their effects on lung gas exchange [23].

Congenital Diseases

Congenital lung malformations are rare abnormalities formed before birth [24] and include pulmonary arteriovenous malformations, congenital lung malformations and congenital diaphragmatic hernias. These malformations can demonstrate an unusual uptake pattern of injected or inhaled radiopharmaceuticals.

Lung Aspiration

Salivagrams assess pulmonary aspiration from refluxed saliva [3]. Paediatric patients present with chronic pulmonary disease, recurrent pneumonia or swallowing difficulties. There are two routes of reflux [3]; antegrade originates from the oropharynx and retrograde from the stomach due to severe gastroesophageal reflux [25].

The salivagram allows imaging of radio-labelled saliva aspirating into the child's airways. This is most commonly associated with the antegrade route, which is more likely to lead to pulmonary infections. Positive salivagrams can demonstrate tracer accumulating within the lungs.

PATIENT PREPARATION AND AFTERCARE

Prior to the patient attending for any nuclear medicine exam, it is important to ensure communication with the patient/family on what to expect, as this aids in reducing procedural anxieties and stress [26]. This can be done by sending information leaflets to the parent/carer prior to attendance; additionally, easy-read comic-style leaflets can be a tool for initial explanation to the patient themselves.

When the patient has arrived, the procedure and any risks/benefits should be thoroughly explained to both the patient and their parents/carers, tailoring communication to the age of the child. Analogies can be used to enable understanding [27], e.g. 'keeping as still as a statue'. Unless contraindicated clinically, the feed and wrap technique should be used for neonates and babies [28]. The breathing mask used to ventilate should be applied gently.

As part of the preparation for intravenous (IV) access, a topical anaesthetic such as a cream or gel should be offered, triggering vasodilatation and reducing pain caused by venepuncture [29].

During the imaging, devices such as the MedVac® vacuum splints [30] can reduce motion artefacts. Use of immobilisation devices should be discussed with the parent or carers and explained to the patient prior to use. Distractions such as books, videos, toys, immersive lights or sensory distraction can help achieve compliance.

Post-radioactive administration, precautions are observed for 24 hours. The main precaution is potential contamination via radioactive urine; if the patient still wears a nappy, parents should be advised to throw sealed nappies into outside bins and ensure thorough hand washing. If the patient is toilet trained, they should use the toilet sitting down and flush twice. Additionally, increasing patient fluid will increase rate of excretion, reducing the patient dose. Avoiding close contact with pregnant persons for 12 hours is advised.

RADIOPHARMACEUTICALS Ventilation

For the ventilation component of V/Q imaging studies, there are several different radiopharmaceuticals available for routine clinical use; a summary is shown in Table 1. [^{99m}Tc]Tc-DTPA particles, due to their larger size, can have lower penetration to

the peripheral airways within the lungs [34], as demonstrated in Figure 1. In patients with narrowed airways, the aerosol is retained and deposited within the central airways, such as in cases of obstructive lung disease [35]. The risk of hot-spot formation is greatly reduced (albeit not totally eliminated) with [^{99m}Tc].

Tc-Technegas [36] — almost all [^{99m}Tc] Tc-Technegas activity reaches past the 16th

Study	Radiopharmaceutical	Physical Form + Particle Size (µm)	Half-Life	Method of Generation + Administration Technique	Administered Activity	Critical Organ (mGy/MBq)	Effective Dose (mSv/MBq)
Ventilation	[^{99m} Tc]-diethylenetriaminepentaacetate (DTPA)	Aerosol (1–3)	6.01 hrs	Diluted in 2 mL water in nebulizer; inhaled for about 2 minutes before imaging	0.4–0.6 MBq/kg administered [33]	0.12 (bladder)	0.020
Ventilation	^{99m} Tc-Technegas	Aerosol (0.005–0.2)	6.01 hrs	Liquid [^{99m} Tc]-pertechnetate aerosolized in Technegas generator, then inhaled for 1–3 breath cycles before imaging	EANM Paediatric Dosage Card (version 5.7.2016): Class B, baseline activity 49 MBq; minimum crucible loading activity 100 MBq [39] Or 0.4–0.6 MBq/kg administered [33]	0.22–0.63 (lungs)	0.031–0.087
Ventilation	^{81m} Kr (Krypton)	Gas	13 secs	⁸¹ Rubidium generator decays to ^{81m} Kr, which is continuously inhaled throughout imaging	0.5–5.0 MBq/kg administered [33]	0.00068 (lungs)	0.00009
Perfusion	^{99m} Tc-MAA	Liquid suspension (10–100)	6.01 hrs	Eluate from ⁹⁹ Mo/ ^{99m} Tc generator used to prepare multidose kit; IV injection before imaging	EANM Paediatric Dosage Card (version 5.7.2016): Class B, baseline activity 5.6 MBq; minimum 10 MBq; calculated activity up to 78.4 MBq at 68 kg [39] Or 1.1 MBq/kg if no ^{99m} Tc ventilation study is performed (minimum 15 MBq), or 2.6 MBq/kg when perfusion follows ^{99m} Tc ventilation [33]	0.13–0.39 (lungs)	0.023–0.063

Table 1. Table of ventilation and perfusion radiopharmaceutical agents, providing a summary of physical characteristics and administration method.

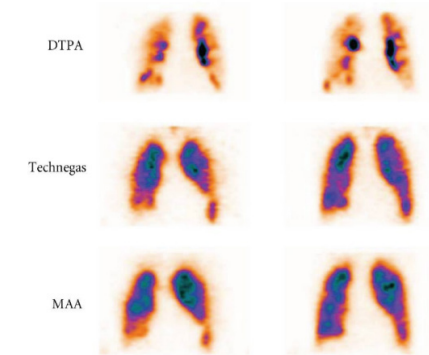


Figure 1. Comparative distribution of ventilation agents vs. perfusion in obstructive lung disease [34].

division of the bronchial tree [31]. As a true gas, ^{81m}Kr distributes evenly throughout the lungs in a similar fashion to air [37]. Due to the very short half-life of ^{81m}Kr , the patient must inhale the gas throughout imaging [37]. For paediatric patients, ^{81m}Kr enables a reduced ventilation dose but at the cost of wearing the mask throughout administration.

PERFUSION

To assess regional lung perfusion, [^{99m}Tc]Tc-MAA is used ubiquitously. Given intravenously, [^{99m}Tc]Tc-MAA is a suspension of aggregated albumin, derived from human serum; due to this, V/Q scans are contraindicated in patients with an allergy or hypersensitivity to products containing human serum albumin [31]. These particles embolise microscopic blood vessels within the pulmonary capillary bed, becoming trapped. As a result, uptake is proportional to the number of particles that reach the capillaries in each lung segment. Therefore, any areas that are receiving less blood flow will appear as photopenic defects.

Aspiration Studies (Salivagram)

To assess pulmonary aspiration, [^{99m}Tc]Tc-sulphur colloid is used. The radiopharmaceutical is diluted in saline and then administered on the tongue, where it mixes with saliva. Once swallowed, any aspirated material will be visible throughout the airways to the lungs [38].

ACTIVITY AND VOLUME ADMINISTERED V/Q Scan

The activity administered using technetium-based aerosols must be carefully controlled: a minimum ratio of 3:1 between perfusion and ventilation counts is needed [17]. A minimum of 10MBq is required to produce images of sufficient quality, based on the count statistics within the imaging time [31].

For [^{99m}Tc]Tc-DTPA aerosol administration, only around one tenth of the nebulised tracer is retained: the nebuliser is therefore loaded with up to 15 times as much as the administered activity. Younger patients and infants can be fitted with an oxygen mask to cover both their nose and mouth, whereas older children can breathe through a mouthpiece with a nose clip attached. General plastic filters can be used to capture exhaled particles.

In the case of [^{99m}Tc]Tc-Technegas, pertechnetate is loaded into the graphite crucible [32]. For pediatric patients, the EANM Paediatric Dosage Card (5.7.2016 version) recommends a minimum crucible loading activity of 100 MBq [39]. As the generator only permits administration within 10 minutes post-heating, the patient should be familiarised with the specialised breathing apparatus beforehand; this excludes very young children, who will

be unable to comply with the breathing instructions. Due to the increased risk of aerosol contamination from poor patient compliance, it is recommended to administer [^{99m}Tc]Tc-Technegas in a separate room. Lying supine, the patient is asked to inhale slowly and deeply, at which point the [^{99m}Tc]Tc-Technegas is delivered. Once the patient has held their breath for 5 seconds, they exhale back through the breathing apparatus. A dosimeter can be used until a sufficient count rate is attained (between 1–1.5 Kcts per second) [32].

^{81m}Kr gas is eluted from the generator at a flow rate of 1–2 litres per minute, which is connected to an oxygen mask placed over the patient's mouth and nose. Due to the short half-life of ^{81m}Kr , the tubing should be kept below 3 metres in length. For young children and infants, the mask will need to be held in place to ensure a good seal. Exhaled gas should be directed away from the detector.

The activity administered for the perfusion study is scaled to the patient's body weight or body surface area using tools such as the EANM Paediatric Dose Card (5.7.2016 version) [39]. Additionally, consideration must also be given to the total number of particles administered. To avoid microembolisation of an excessive number of capillary vessels (no more than 0.1%), the number of particles given will need to be set according to body weight [31]. The concentration of particles per MBq should be calculated in conjunction with the time of injection when preparing the [^{99m}Tc]Tc-MAA. Furthermore, the number of particles will need to be reduced in cases of PH, right-left shunts, and cases where there is a severe reduction in the number of pulmonary capillaries, e.g. pneumonectomy or solitary lung transplant [40].

Aspiration Studies (Salivagram)

Salivagrams require only a small activity of [^{99m}Tc]Tc-sulphur colloid, scaled to body weight. Studies have been performed using around 7–11 MBq diluted in a volume of around 100 μL [38]. Other more recent protocols have used 0.55 MBq/kg, where up to 37 MBq has been given in a volume of 1 mL [3].

INJECTION TECHNIQUE

As [^{99m}Tc]Tc-MAA is a suspension, macroaggregates settle to the bottom over time. Gently inverting the vial several times before drawing up will homogenise the mixture. Additionally, the time between drawing up a dose and administration should be minimised due to particles sticking to the inside of the plastic syringe [31]. The syringe should then be inverted several times just prior to administration.

The patient should be supine for both inhalation and perfusion administration, as this provides the most representative distribution; upright administration should be avoided as gravity will draw disproportionately more of the tracer towards the lung base.

When injecting, blood should not be withdrawn into the tracer syringe as radiolabelled aggregations can form inside the syringe; these then appear as hot spots within the lungs (Figure 2), thereby potentially indicating a false-positive diagnosis. Residual activity can be reduced by repeated saline flushes via the tracer syringe. Injecting steadily over the course of multiple breaths (around 30 seconds) will ensure even distribution.

Either a venous cannula or a winged infusion needle (butterfly) should be sited, depending on vein access/frailty and patient tolerance. Long central lines such

as peripherally inserted central catheters (PICCs) and central venous catheters (CVCs) should be avoided, as [^{99m}Tc]-MAA will adhere to the inner wall — leaving an artefact and increasing the chance of aggregations forming, as seen in Figure 2.

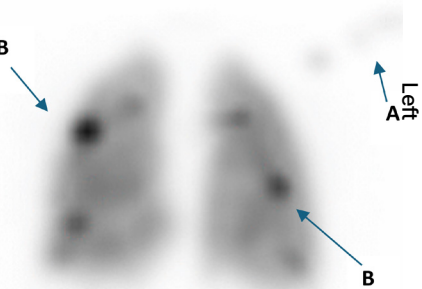


Figure 2. Lung V/Q SPECT showing (A) [^{99m}Tc]-MAA trapped inside the lumen of CVC. (B) Aggregations of [^{99m}Tc]-MAA resulting from injecting through a central line. Images reproduced courtesy of Great Ormond Street Hospital, London, United Kingdom

IMAGING PROTOCOL AND IMAGING PROCESSING
Planar V/Q Scan

Imaging parameters for V/Q scans are summarised in Table 2. If using [^{99m}Tc]Tc-DTPA or [^{99m}Tc]Tc-Technegas, the ventilation images must be acquired before administering [^{99m}Tc]Tc-MAA. As the photopeak of ^{81m}Kr (190 KeV) is significantly higher than that of ^{99m}Tc (140 KeV), imaging can be performed in any desired order or in a simultaneous dual-energy acquisition [31]. The patient is positioned with the lungs fully visible within the field of view, with an appropriate zoom. A detector angle of 35–45 degrees is used for the oblique views, ensuring no overlap of the lungs (optional when only a split lung perfusion calculation is needed).

Imaging Technique		Collimator	Acquired View(s)	Acquisition Counts/ Time	Matrix Size
Planar	Ventilation	LEHR (MELP if using ^{81m} Kr)	Anterior, Posterior, Left and Right obliques	200 KCounts	128×128
	Perfusion		Anterior, Posterior, Left and Right obliques	Ideally 350–500 KCounts, min. 200 KCounts	128×128
	Right-Left shunt	LEHR	Whole-body sweep	30 cm/min	256×1024
SPECT	Ventilation	LEGP	~120 projections over 360 degrees	10 seconds per view	64×64
	Perfusion			5 seconds per view	64×64

Table 2. Table summarising gamma camera parameters for V/Q imaging [17], [31], [37], [41], [42].

Planar images are displayed for qualitative analysis as rows of corresponding ventilation and perfusion images. Using the anterior and posterior statics, a geometric mean can be calculated to determine the ratio of counts between each lung [31]. To quantify right-left shunts the whole-body sweep image is used to draw regions of interest (ROIs) around the brain, kidneys and spleen, and another around the lungs [43]. The shunting can then be expressed as a percentage of total counts, i.e. other organs plus lungs, versus the counts in the lungs only [44].

SPECT (/CT)

Low-energy general-purpose (LEGP) is the preferred collimator due to its increased sensitivity. For ^{99m}Tc-based agents, the ventilation SPECT is acquired first. To ensure good registration, the patient is kept in the same position for the injection of [^{99m}Tc]Tc-MAA, followed by a second SPECT. ^{81m}Kr gas allows for a single dual-energy SPECT acquisition [45]. However, SPECT±CT imaging requires a higher level of cooperation from the child to minimise artefacts, and therefore its use also depends on the clinical presentation.

Iterative reconstruction should be used to reconstruct the raw data, using algorithms such as OSEM (ordered subset expectation maximisation) [41]. The reconstructed data can then be displayed, aligning the ventilation and perfusion data sets; misregistration will need to be carefully corrected before analysis. Images are presented as slices through the coronal, sagittal, and axial planes; triangulation can then be used to pinpoint defects. V/Q quotient images, consisting of the

ventilation counts fused and normalised to the perfusion counts, can help quantify the extent of defects. These quotient images highlight areas of greatest difference between the two scans based on the ratio of counts [42,46].

Aspiration Studies (Salivagram)

The patient is positioned supine on the imaging couch, with the field of view covering mouth to upper abdomen. The radiopharmaceutical is administered and a dynamic acquisition for 1 hour with 30-second frames is obtained immediately afterwards [38]. A higher-sensitivity collimator such as LEGP is recommended, with a 140 KeV ±7.5–10% window. A post-dynamic 5-minute static can also be acquired [3]. Radioactive markers, placed on the suprasternal notch and collarbone, help correlate with anatomy. Dynamic images are displayed in a suitable grouping in chronological order.

IMAGE INTERPRETATION
V/Q Scan

Interpretation of V/Q images is greatly aided by anatomical contextualisation, so a recent chest x-ray should be available [31] as well as other clinically relevant data, e.g. D-dimer. Differences in tracer distribution between the ventilation and perfusion scans can be identified as either matched, mismatched, or reverse mismatched (see Clinical Cases section for examples).

Segmental lung map diagrams are used to describe the anatomical location, extent and number of abnormalities (Figure 3). Recognising pathological defects on paediatric scans is made more difficult

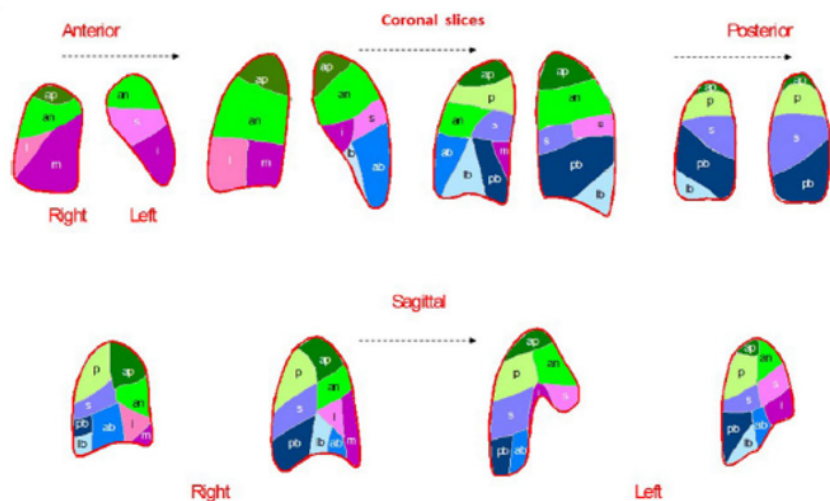


Figure 3. Segmental lung map [18].

by the greater variation in lung anatomy compared to adults. Additionally, identifying the segmental locations of defects can be hampered by altered lung contours caused by congenital conditions.

With matched defects, the same area of the lung will be photopenic on both ventilation and perfusion imaging; they are typically found because of a collapsed lung and/or collection of fluid in the pleural spaces. Reverse mismatches occur where there is a greater reduction in ventilation compared to perfusion and are indicative of COPD. Both matched and unmatched defects can also be found at different stages of pneumonia, identifiable by a 'stripe sign' where there is a thin line of perfused tissue past the defect at the lung periphery. Acute PE can be diagnosed by the presence of a minimum of 1 mismatched segmental defect or two sub-segmental defects, appearing as wedge-shaped areas of reduced perfusion.

with normal ventilation [17]. Mismatched non-segmental defects may be due to previous partly resolved PE or unrelated conditions such as heart failure [17].

Aspiration Studies (Salivagram)

Salivagram interpretation is purely qualitative, the images being visually reviewed to identify any activity outside of the upper gastrointestinal tract, as shown in Figure 4. Normal scans show activity transiting from the mouth through the midline (oesophagus) until it enters the stomach, whereas aspiration can be identified by movement of the tracer lateral to the mid-oesophageal level, representing bronchial uptake. Uptake can be either unilateral or bilateral and is graded depending on the degree of extension through the proximal bronchi into the more peripheral airways [38].

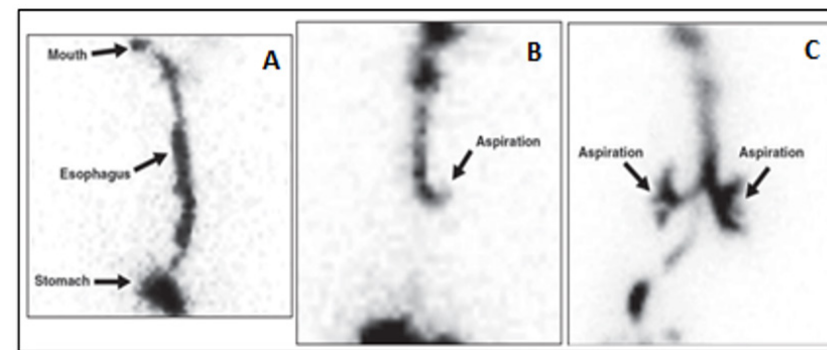


Figure 4. (A) Negative salivagram showing swallowed activity moving through the oesophagus to the stomach. (B) Low-grade aspiration into the left proximal bronchi. (C) Extensive bilateral bronchial aspiration [38].

CLINICAL CASES

Pulmonary Embolism

A 17-year-old patient attended for an annual V/Q scan due to being on long-term home parenteral nutrition [47] and currently experiencing intestinal failure. Planar perfusion and ventilation images were taken. Figure 5 shows multiple bilateral segmental mismatched perfusion defects consistent with PE. Oral warfarin was started, and a D-dimer test showed slightly

elevated levels. A repeat V/Q was performed 3 months later, showing full resolution of PE.

Pre-Operative

A 9-year-old patient presented with interatrial communication from arterial septal defect (ASD), PH (potentially from ASD) and occlusion of the left pulmonary artery. Patient was transferred from local hospital with no previous medical records. Patient was referred for V/Q scan with SPECT/CT to

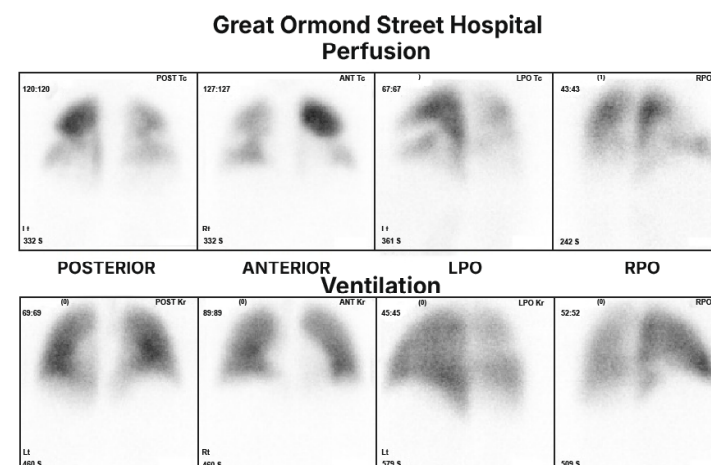


Figure 5. Planar V/Q scan demonstrating [te2.1] multiple bilateral segmental mismatched perfusion defects. Images reproduced courtesy of Great Ormond Street Hospital, London, United Kingdom

assess left pulmonary artery obstruction and work-up for potential lung transplant.

Planar V/Q and perfusion SPECT/CT (Figure 6) demonstrate extremely poor perfusion to the left lung and almost absent perfusion to the right upper lobe. Poor perfusion noted in the right middle lobe medially; this correlates with an incomplete horizontal fissure, as seen on the CT. Poor left lung perfusion is in keeping with truncated left pulmonary artery. Left lung also shows reduced global ventilation. Patient admitted onto lung transplant list.

Shunting

An 8-year-old patient presented with hypoplastic left heart syndrome and congenital hypoplasia of left pulmonary artery. Had previously undergone an aortic correction, presented prior to planned Fontan procedure to re-route inferior and superior vena cava to the pulmonary arteries. CT and V/Q scans were performed to assess lung anatomy and function. Planar V/Q scan, Figure 7, showed perfusion tracer in the kidneys, spleen and brain,

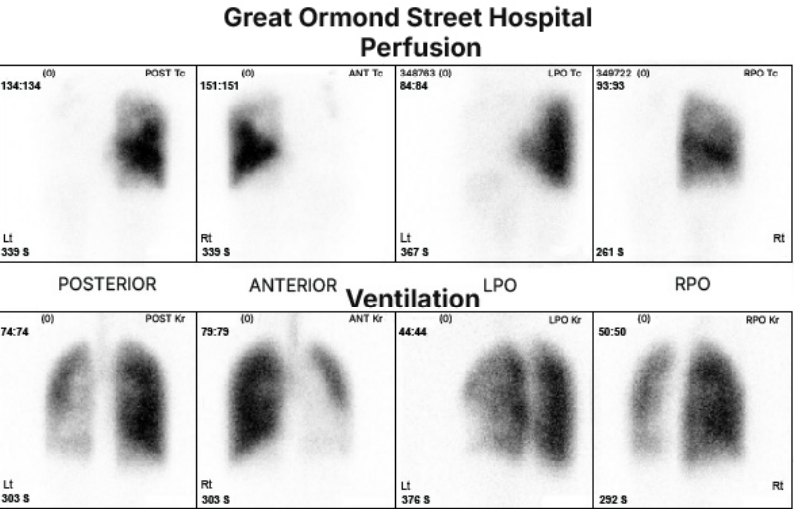


Figure 6. Perfusion SPECT/CT and planar V/Q[te3.1] images demonstrating occluded left pulmonary artery. Images reproduced courtesy of Great Ormond Street Hospital, London, United Kingdom

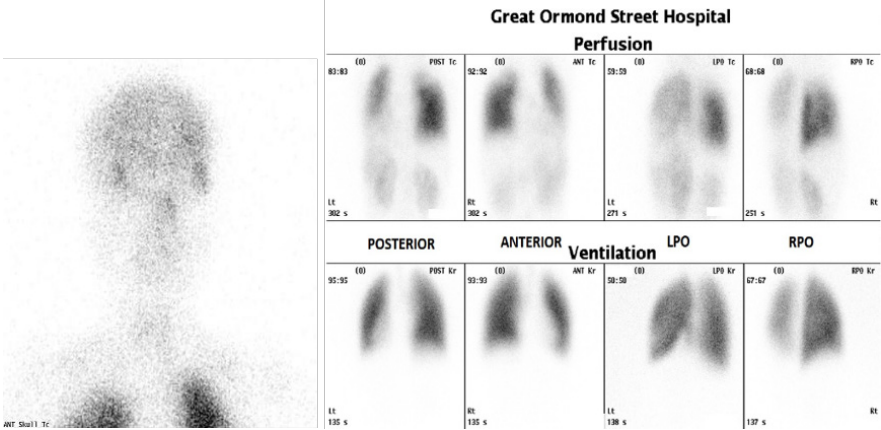


Figure 7. Planar V/Q scan demonstrating[te4.1] significant right-to-left shunt. Images reproduced courtesy of Great Ormond Street Hospital, London, United Kingdom

demonstrating significant right-to-left shunt (superior vena cava to inferior vena cava shunt).

Results indicated additional global reduced perfusion to the left lung with a focal defect. Reduced ventilation in lower left lobe correlates with CT finding of extensive mucous plugging. Patient underwent complex Fontan cardiac surgery, requiring prolonged hospital admission. Procedure was successfully performed and patient discharged.

Congenital Abnormality

Sixteen-year-old patient with horseshoe lung, V/Q scan requested to assess pre-operatively. The perfusion SPECT/CT and planar V/Q studies, Figure 8, demonstrate that the horseshoe segment of the right lung extending into the left hemithorax does not contribute to gas exchange, resulting in both poor ventilation and perfusion. The CT

component demonstrates hyperlucency and reduced vasculature.

The cardio-thoracic team proceeded with a surgical bullectomy (removing damaged bullae) and pleurectomy with pleurodesis, sealing the space between lung and chest wall, to prevent recurrent pneumothorax on the right side. The left side of the lung was left to behave as a prosthesis. The surgical intervention was successful.

CONCLUSION

In conclusion, paediatric lung scintigraphy is a safe, sensitive and specific mode of imaging used to diagnose a range of paediatric conditions, including congenital, chronic and acute pathologies. The combined usage of CT with SPECT allows more accurate reporting, and if performed together can allow a one-stop shop for paediatric imaging.

Special consideration should be given to preparation when imaging children,

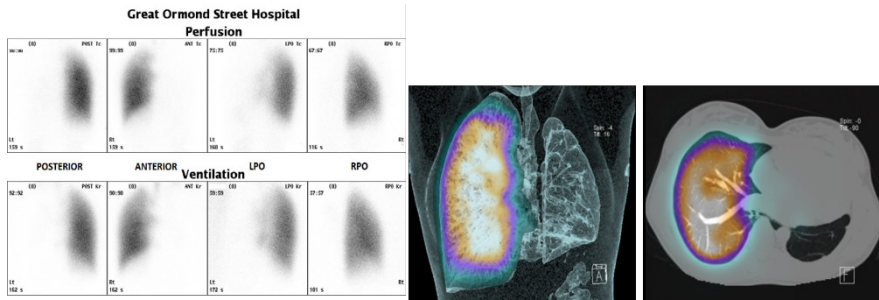


Figure 8. Perfusion SPECT/CT and planar V/Q demonstrating horseshoe lung function. Images reproduced courtesy of Great Ormond Street Hospital, London, United Kingdom

ensuring appropriate explanations to both the child and their accompanying parents/carers. Additional support should be given with distraction techniques, play and immobilisation to achieve high-quality images.

When performing V/Q scans in children, thought must be given to the radiopharmaceuticals administered, as patient tolerance and radiation dose should be kept as low as reasonably practicable. Administration techniques can vary, but ensuring appropriate support to the patient can help achieve good-quality diagnostic images.

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HIDA – Biliary Atresia

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EXECUTIVE SUMMARY

The Hepatobiliary Iminodiacetic Acid (HIDA) scan is a decisive and non-invasive procedure for evaluating neonatal cholestasis, with its most critical role being the differentiation of biliary atresia from other causes. Biliary atresia is a progressive condition requiring prompt surgical intervention, making accurate diagnosis essential.

The procedure hinges on the administration of a HIDA radiopharmaceutical, such as [^{99m}Tc] Tc-Mebrofenin, which is taken up by hepatocytes and excreted into the biliary system. Meticulous patient preparation, including fasting and pre-treatment with phenobarbital or recommended alternatives to enhance hepatobiliary excretion, is fundamental to diagnostic accuracy.

The key scintigraphy finding is the absence of tracer excretion into the bowel at 24 hours post-administration. Consequently, this result is a critical indicator that makes a timely surgical referral imperative to prevent further liver damage. This protocol represents the standard of care in the diagnostic workup of infantile jaundice, enabling precise diagnosis and guiding timely management for improved patient outcomes.

Keywords: Biliary Atresia; Neonatal Cholestasis; HIDA Scan; Hepatobiliary Scintigraphy; [^{99m}Tc]Tc-Mebrofenin; Ursodeoxycholic Acid (UDCA); Phenobarbital.

INTRODUCTION

The development of hepatobiliary imaging began in 1923 through the use of rose bengal, a dye used for liver function tests. In 1955, it was labelled with radioactive iodine-131 (^{131}I), allowing external tracking of its pathway and differentiation of liver diseases through gamma counting, which later evolved into functional imaging [2].

A major advance occurred in the 1970s with the introduction of [^{99m}Tc]Tc-labelled compounds, specifically hepato-iminodiacetic acid (HIDA), which offered significant improvements over rose bengal [2, 3]. However, early versions like lidofenin performed poorly in patients with high bilirubin levels.

Further refinements led to the development and Food and Drug Administration (FDA) approval of two superior agents that remain in common use today: [^{99m}Tc]Tc-Disofenin (2, 6-diisopropylacetanilido iminodiacetic acid) in 1992 and [^{99m}Tc]Tc-Mebrofenin (bromo2, 4, 6-trimethylacetanilido iminodiacetic acid) in 1993 [12]. The term HIDA is now synonymous with hepatobiliary scintigraphy using these radiopharmaceuticals.

The evolution of these radiopharmaceuticals provided a safe and dynamic method to visualise bile production and flow through the biliary system into the small intestine. For the paediatric population, this became an indispensable tool to investigate neonatal cholestasis, a condition where an impaired bile flow into the intestines results in jaundice. The most serious cause of obstructive cholestasis is biliary atresia, a rare and destructive inflammatory condition that obliterates varying lengths of a neonate's intrahepatic and extrahepatic bile ducts [14]. While once fatal, effective palliative surgery (Kasai portoenterostomy)

within the first 2 to 3 months of life allows infants to grow and eventually receive curative liver transplantation. This is dependent on early referral and timely intervention. Without any treatment, progressive liver cirrhosis leads to death typically by 2 years of age [4,5].

The fundamental mechanism of the HIDA scan relies on the extraction of the radiopharmaceutical from the bloodstream by hepatocytes via active, carrier-mediated transport pathways that closely parallel those used for unconjugated bilirubin. This happens specifically at the hepatocyte's sinusoidal membrane, utilising organic anion-transporting polypeptides (OATPs), the same transport system involved in bilirubin handling. After intravenous administration, the tracer traverses the hepatocyte and is excreted into the biliary canaliculi via canalicular transporters, without requiring intracellular conjugation. It then follows the physiological flow of bile through the intrahepatic ducts, common hepatic duct, gallbladder, common bile duct, and finally into the duodenum and small bowel [6].

In biliary atresia, the functional obstruction prevents the tracer from reaching the bowel, producing an abnormal scintigraphic pattern. The technologist's expertise is critical in performing this study with precision to avoid false-positive results, and its role in the management algorithm for neonatal jaundice is well established [7, 8].

CLINICAL INDICATIONS AND CONTRAINDICATIONS

The primary clinical indication for a HIDA scan in a neonate is to differentiate biliary atresia from other causes of neonatal cholestasis, such as neonatal hepatitis or

paucity of intralobular bile ducts [9]. The clinical scenario is typically an infant, 2–8 weeks old, with persistent jaundice, dark urine, acholic (pale) stools, and elevated conjugated bilirubin [10].

Indications

» Evaluation of neonatal cholestasis with suspected biliary atresia [9, 10, 11]

» Assessment of post-surgical biliary patency following Kasai portoenterostomy for biliary atresia [9, 12]

» Investigation of other biliary tract anomalies (such as choledochal cysts, bile duct leaks, bile-plug syndrome, paucity of intralobular bile ducts, etc.) in the paediatric population [13]

Contraindications

There are no absolute contraindications to hepatobiliary scintigraphy for this clinical indication. However, the following relative contraindications and important considerations should be noted:

» Severe hypersensitivity to the HIDA derivatives is a theoretical concern but is exceedingly rare [14]

» The benefits of the procedure must always be weighed against the radiation exposure, adhering to the As Low As Reasonably Practicable (ALARP) principle. The effective dose for a neonatal HIDA scan is low and is justified by the critical diagnostic information it provides [14, 15]

PATIENT PREPARATION AND AFTERCARE

Proper patient preparation is arguably the most critical step to ensure a diagnostic study. Inadequate preparation is a common cause of false-positive results (simulating obstruction).

The infant should fast for 2 to 4 hours prior to the radiopharmaceutical injection. This is essential because fasting minimises potential interference from dietary substances in the imaging, allows the gallbladder to fill with bile in preparation for the test, and primes the body to release cholecystokinin (CCK) once feeding resumes. The release of CCK is the key event, as it stimulates the gallbladder to contract and optimises biliary flow, which carries the tracer through the system to produce a clear and diagnostically useful scan [2, 9, 16, 17]. A practical way to accomplish this is to coordinate the scan with the infant's feeding schedule. A feed around 2 hours before the injection of the tracer is ideal. Shorter fasting periods may not adequately stimulate the biliary system, while prolonged fasting can lead to sluggish bile flow.

Pre-treatment is mandatory when investigating for biliary atresia as it stimulates hepatic bilirubin metabolism and biliary excretion, which in turn improves tracer clearance and significantly enhances the sensitivity and specificity of the study [18]. Ursodeoxycholic acid (UDCA) is the preferred pre-treatment, as it offers a shorter preparation period and a more favourable side-effect profile compared to phenobarbital. The recommended directive is 20 mg/kg orally every 12 hours for 2–3 days prior to the scan [12].

Alternatively, phenobarbital, a microsomal enzyme, may be used, particularly if UDCA is not available. The standard dosage is 5 mg/kg/day orally, divided into two daily doses, administered for 3–5 days prior to the scan and discontinued after tracer injection [9, 12, 18, 19]. Caregivers should be advised to monitor the child for potential phenobarbital-related side effects, most commonly drowsiness or sedation. Medical attention should be sought if the child experiences excessive lethargy, difficulty breathing, rash, or significant unsteadiness. Confirming that the phenobarbital has been administered as prescribed is important. Documentation of the duration and dose in the patient's file is also good practice, as without pre-treatment the study's diagnostic value is significantly compromised.

Additionally, effective communication between the team of nuclear medicine technologists and parents or caregivers is crucial for positive patient outcomes, as it fosters trust and understanding. Parents or caregivers should receive a clear explanation of the entire procedure, including extended imaging times (up to 24 hours), the importance of the infant remaining still, and the safety of the administered radioactive dose. Engaging caregivers throughout the procedure with the child is essential. A calm and well-informed parent can be very helpful in soothing the infant during the scan [20].

After the imaging is complete, caregivers can be reassured that the radioactive tracer will decay and be excreted naturally, posing no risk to the infant or family members. Normal feeding and care should be encouraged. The study results should then be communicated to the referring physician.

RADIOPHARMACEUTICAL

The radiopharmaceutical of choice for neonatal HIDA scans is [^{99m}Tc]Tc-Mebrofenin. Other agents such as [^{99m}Tc]Tc-Disofenin can be used, however Mebrofenin is preferred in neonates due to its higher first-pass hepatic extraction fraction (~98%), achieved via active transport into hepatocytes by organic anion transporters shared with bilirubin [21]. This allows rapid blood clearance, minimal urinary excretion, and direct biliary excretion without conjugation, making it uniquely reliable for functional imaging even in patients with significant hyperbilirubinemia [21, 22]. As bilirubin competes with the HIDA tracer for hepatocyte uptake, mebrofenin's superior extraction provides better target-to-background ratios, which is crucial for diagnostic image quality in a jaundiced infant.

These robust pharmacokinetic properties allow for a definitive functional assessment where the presence of rapid biliary flow into the intestines rules out biliary atresia, making it a critical tool for this essential differential diagnosis [23].

In the context of mebrofenin supply disruptions, which have been reported in several countries, the use of alternative hepatobiliary radiopharmaceuticals may be necessary. ^{99m}Tc -Disofenin remains a valid alternative and shares the same hepatocyte uptake mechanism via organic anion transporters. However, its slightly lower first-pass hepatic extraction fraction (~88%) makes it more susceptible to competition from bilirubin, potentially resulting in delayed hepatic uptake and poorer target-to-background ratios in jaundiced neonates [21]. Other IDA derivatives, such as [^{99m}Tc]Tc-Lidofenin, have been used historically but demonstrate even lower hepatic

extraction and higher urinary excretion, which can complicate image interpretation in suspected biliary atresia. Therefore, while these agents may be employed when mebrofenin is unavailable, users should be aware that image quality and diagnostic confidence may be compromised, particularly in infants with marked hyperbilirubinemia. If an alternative agent must be used, extending the acquisition protocol to account for delayed tracer handling should be considered, and findings should be interpreted with appropriate caution.

ACTIVITY AND VOLUME ADMINISTERED

In the paediatric population, calculating the appropriate administered activity is critical. The goal is to administer the minimum activity required to obtain a diagnostically useful study while adhering to the fundamental principles of radiation protection, specifically the ALARP principle [15].

Unlike adult dosing, which often uses a fixed activity, paediatric dosing must be carefully adjusted according to the child's body weight or body surface area. Major international bodies, such as the EANM, the Society of Nuclear Medicine and Molecular Imaging (SNMMI) and the Administration of Radioactive Substances Advisory Committee (ARSAC) in the UK, provide established guidelines for this purpose.

The EANM has developed a weight-based system for radiopharmaceuticals used in paediatrics, which offers a quick reference for calculating the administered activity [15, 24]. This system helps to produce images with an image quality and an imaging time comparable to that expected

for adults, by maintaining the same image count density. Clinical protocols should state clearly how the fraction of adult administered activity is applied to children and adolescents, as per national regulations such as those from ARSAC [25].

According to the 5.7.2016 version of the EANM paediatric dosage card, the recommended activity for a HIDA scan is 1.85 MBq/kg (0.05 mCi/kg), with a minimum activity of 20 MBq (0.54 mCi) and a maximum activity of 150 MBq (4.05 mCi), equivalent to the adult activity [15, 24]. This also aligns with the North American guidelines [12, 26].

The injection volume should be as small as possible, typically 0.1–0.3 mL, to facilitate a clean bolus injection and minimise the risk of extravasation. The intravenous (IV) line should be flushed thoroughly with saline to ensure that the entire activity is administered.

INJECTION TECHNIQUE

Establishing a secure IV line is the crucial and often most challenging step in paediatric procedures, requiring a careful approach to minimise trauma and improve patient cooperation. Adequate preparation is key and involves pre-planning venous access, applying lidocaine and prilocaine anaesthetic cream at least 1 hour in advance, and using positive reinforcement [20].

A small-gauge (24–26G) cannula should be placed in the upper limb or foot, avoiding areas adjacent to joints in order to prevent accidental dislodging, potentially leading to extravasation and the need for additional punctures. Direct injection is discouraged, and a cannula is normally preferred since it is more stable, leading to a higher chance

of successful administration. Throughout the procedure, distraction techniques and caregiver support are invaluable for managing anxiety and discomfort [20].

Prior to injection, the line should be flushed with saline to confirm patency and rule out infiltration. Effective limb immobilisation is a determining factor for successful administration. Parents can assist with this, as their presence helps the infant feel safer and more relaxed [20]. Following the confirmation saline flush, the radiopharmaceutical can be administered as a compact bolus, starting dynamic acquisition simultaneously.

To prevent accidental dislodgement and allow continuous observation for extravasation, a transparent dressing or bandage should be placed over the cannula, leaving the access hub visible. This is particularly important in infants, who cannot communicate discomfort. Careful monitoring of the injection site throughout tracer administration is essential.

IMAGING PROTOCOL

A standardised imaging protocol is essential for achieving consistent and interpretable results, as outlined in guidelines from professional societies such as the EANM, SNMMI and British Nuclear Medicine Society (BNMS) [12, 17].

Before the scan, the child should be changed into a clean and securely fastened nappy, in order to prevent leaks. To promote natural sleep during imaging, parents can be advised to keep the infant awake beforehand. Effective techniques include feeding as close as possible to the 2 hours of fasting period scan time, comfortable swaddling once placed on the camera bed, and dimming of room lights. It is essential that the infant remains as still as possible.

Creating a calm, friendly environment may enhance the child's comfort and cooperation before and during the procedure. Detailed handling protocols are available in dedicated guides, such as the EANM procedural recommendations for managing the paediatric patient in diagnostic nuclear medicine [20].

The infant should be positioned supine and centred under the gamma-camera detector. To ensure comfort and immobility without distress, the use of soft restraints and padding is recommended. All images are to be acquired from an anterior view, with the detector positioned as close as possible to the patient.

The gamma camera needs to be set up with a low-energy high-resolution (LEHR) or a low-energy general-purpose (LEGP) parallel-hole collimator. The latest scanners feature new parallel-hole collimator designs, such as low-energy high-resolution and sensitivity (LEHRS), which help to reduce scan times. The energy window should be centred on the ^{99m}Tc energy peak of 140 keV $\pm$ 7.5–15%.

The acquisition protocol begins immediately after injection with a dynamic acquisition of 60 seconds/frame for a total of 60 minutes, with a matrix of 128×128. If excretion is not seen, delayed static images at 2, 4, 6, and 24 hours post-injection should be acquired [12, 17, 27, 28]. The 24-hour image is used in children with no evidence of bowel excretion on the first day of the study. These images can last up to 5 minutes each, and a matrix of 256×256 is the best option. The zoom can be increased to 2.0 throughout all acquisitions as an infant has a small body size. The study can be discontinued at earlier time points if there is clear evidence of tracer accumulation in the bowel.

If available and if excretion is absent at 60 minutes, a SPECT/CT acquisition can be performed. The low-dose CT provides superb anatomical localisation, helping to confirm the presence or absence of activity in the bowel versus uptake in the gallbladder or urinary system, which may be ambiguous on planar imaging [27, 28].

IMAGING PROCESSING

The dynamic study can be reviewed as a cinematic loop. Time-activity curves over the liver and heart can then be generated to provide a semi-quantitative assessment of hepatic extraction. Regions of interest (ROIs) are drawn over the right lobe of the liver to measure uptake and retention and the heart to calculate cardiac blood pool clearance. Another ROI should also be drawn over the small bowel area to detect any potential tracer excretion, and a background ROI to estimate background activity. Good hepatic extraction is seen as rapid clearance of blood-pool (cardiac) activity with a concomitant rise in liver activity [29].

Key considerations for ROI placement

» **Movement exclusion:** The dynamic acquisition should be reviewed for patient motion, which can significantly affect time-activity curves. When motion is detected, the affected frames should be either manually realigned or excluded from the analysis. ROIs may need to be repositioned or drawn on a summed frame to better account for motion.

» **Overlap avoidance:** The liver ROI must not include high activity from adjacent structures such as the bowel, stomach, or duodenum, especially in later frames

when tracer excretion may cause spillover. Similarly, the cardiac ROI should avoid the lung bases or liver dome.

» **Consistency:** The same ROI shape and location should be used across all frames whenever possible. When motion correction is applied, ROIs must be propagated to the aligned frames accordingly.

» **Background placement:** The background ROI should be positioned adjacent to the liver but away from major blood vessels, the gallbladder, or bowel activity to obtain a representative estimate of non-specific activity.

IMAGE INTERPRETATION

A review of relevant imaging together with the patient's clinical history is advised, paying particular attention to details of previous surgeries, which can result in altered anatomy. Accurate image interpretation depends on sound knowledge and extensive experience of the normal range of tracer distribution to help distinguish significant pathology from normal or trivial pathology.

The study is reviewed systematically by the interpreting clinician:

1. **Blood Flow:** Assess for normal perfusion to the liver.
2. **Hepatocellular Function:** Evaluate the rapidity and degree of hepatic extraction. In biliary atresia, extraction is often normal or only mildly delayed.
3. **Biliary Excretion:** This is the core of the study.
 - **Normal Study:** Tracer is seen in the gallbladder and/or small bowel within 60 minutes [12, 17]

◦ **Findings Suggestive of Biliary Atresia:** Good hepatic extraction with no evidence of tracer in the bowel on the 24-hour delayed images [8, 11, 23, 30]. The gallbladder is also typically not visualised

◦ **Neonatal Hepatitis Pattern:** Typically shows delayed and poor hepatic extraction (leading to persistent high blood-pool and renal activity) with eventual, often delayed, excretion into the bowel [8, 11, 22, 31]

◦ Renal or urinary excretion of the tracer, present for example in a nappy, may be confused with bowel activity and is a potential source of erroneous interpretation

While final interpretation is the responsibility of the physician, nuclear medicine technologists must be able to differentiate a normal scan from one that requires further imaging. The presence of bowel activity on the initial dynamic study allows immediate termination of the study, as it rules out biliary atresia. Such a course of action maximises efficiency, especially if the infant is agitated. If bowel activity is absent at 4–6 hours post administration of the radiotracer, the study must be continued to include the 24-hour delayed image.

PATIENT PATHWAY

Hepatobiliary scintigraphy has been an important, clinically useful diagnostic imaging study for almost four decades now, and it continues to be an essential tool for diagnosing biliary atresia. Effective and timely collaboration among departments such as Neonatal Services, paediatric wards, and the Nuclear Medicine team is essential to obtain high-quality diagnostic images.

Following completion of the scan, images are reviewed by a Nuclear Medicine physician and correlated with clinical and laboratory findings. The results are communicated promptly to the referring team, as early diagnosis of biliary atresia is critical for timely surgical intervention. Parents or guardians are informed of the next steps, which may include further imaging, liver biopsy, or referral for surgical management. Clear documentation and multidisciplinary communication are essential to ensure continuity of care and optimal outcomes for the patient.

CLINICAL CASE

Clinical Information:

» Two-week-old infant with persistent and worsening conjugated hyperbilirubinemia

» Clinical suspicion of biliary atresia

Pre-Procedural Planning:

» Appointment scheduled following contact with the parents. Fridays were avoided to accommodate potential 24-hour imaging

» Parents were also informed about required phenobarbital pre-treatment

» Cannulation slot booked in the Children's Day Care Ward

» Patient given oral phenobarbital for 5 days prior to the study (10.5 mg/day, based on 5 mg/kg, divided into two daily doses)

Procedure:

» Patient breastfed, then cannulated in the Children's Day Care Ward

» Nappy changed in Nuclear Medicine department prior to tracer administration

» Tracer administered after confirming ≥ 2 hours nil by mouth and calculating weight-based activity

» 1-hour dynamic study acquired initially (Figure 1)

» Due to no bowel activity, static 5-minute images were taken at 1.5, 2.5, and 3.5 hours (timing adjusted for infant's routine/camera availability)

» 24-hour delayed image acquired the following day (all static images are presented in Figure 2)

Findings:

» Good and homogeneous hepatic uptake

» No bowel activity visualised by 24 hours

» Some bladder activity present throughout the study

» 24-hour hepatic retention with significant uptake, indicating hepatic dysfunction

» Interpretation:

» Study findings are consistent with biliary obstruction

» Biliary atresia is not excluded

» Note: severe hepatic dysfunction can produce a scintigraphic appearance identical to that of biliary atresia.

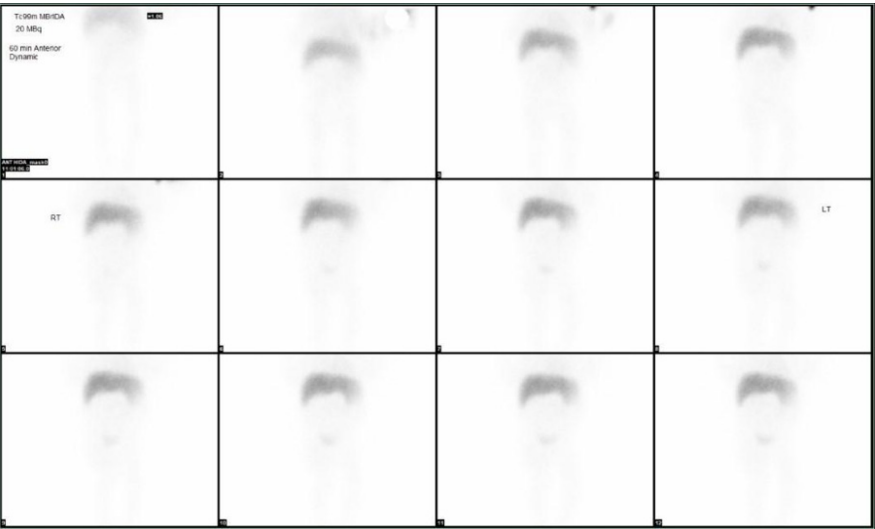


Figure 1. 60-minute dynamic acquisition displayed in 5-minute frames. The featured images are reproduced courtesy of the Oxford University Hospitals – NHS Foundation Trust.

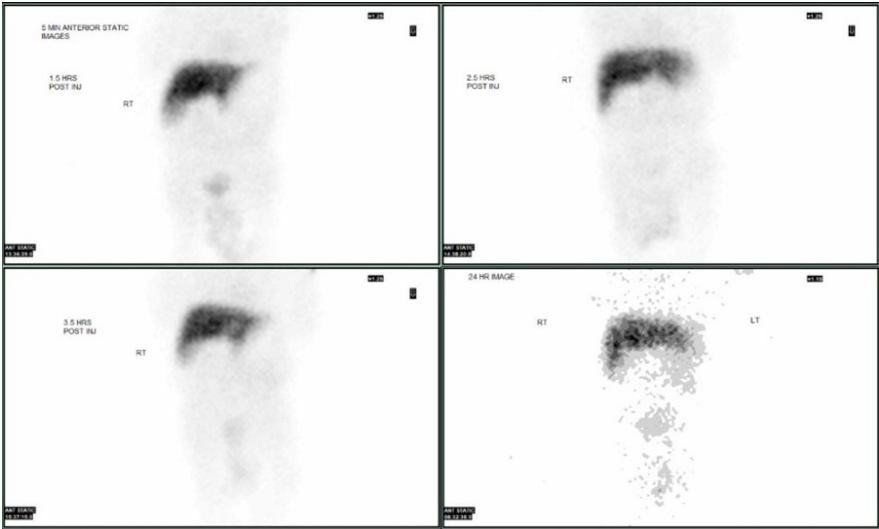


Figure 2. 5-minute static images acquired at 1.5, 2.5, 3.5 and 24 hours post tracer administration. The featured images are reproduced courtesy of the Oxford University Hospitals – NHS Foundation Trust.

CONCLUSION

The HIDA scan remains a vital functional imaging study in the diagnostic algorithm for neonatal cholestasis. Performing this examination requires a blend of technical skill, meticulous attention to detail in patient preparation, and a compassionate approach to handling a vulnerable paediatric patient and their anxious family. Understanding the principles, pitfalls, and practical nuances of the procedure, as guided by current evidence and professional guidelines [17, 25, 15], ensures the acquisition of high-quality, diagnostically decisive images that directly impact patient management and outcomes.

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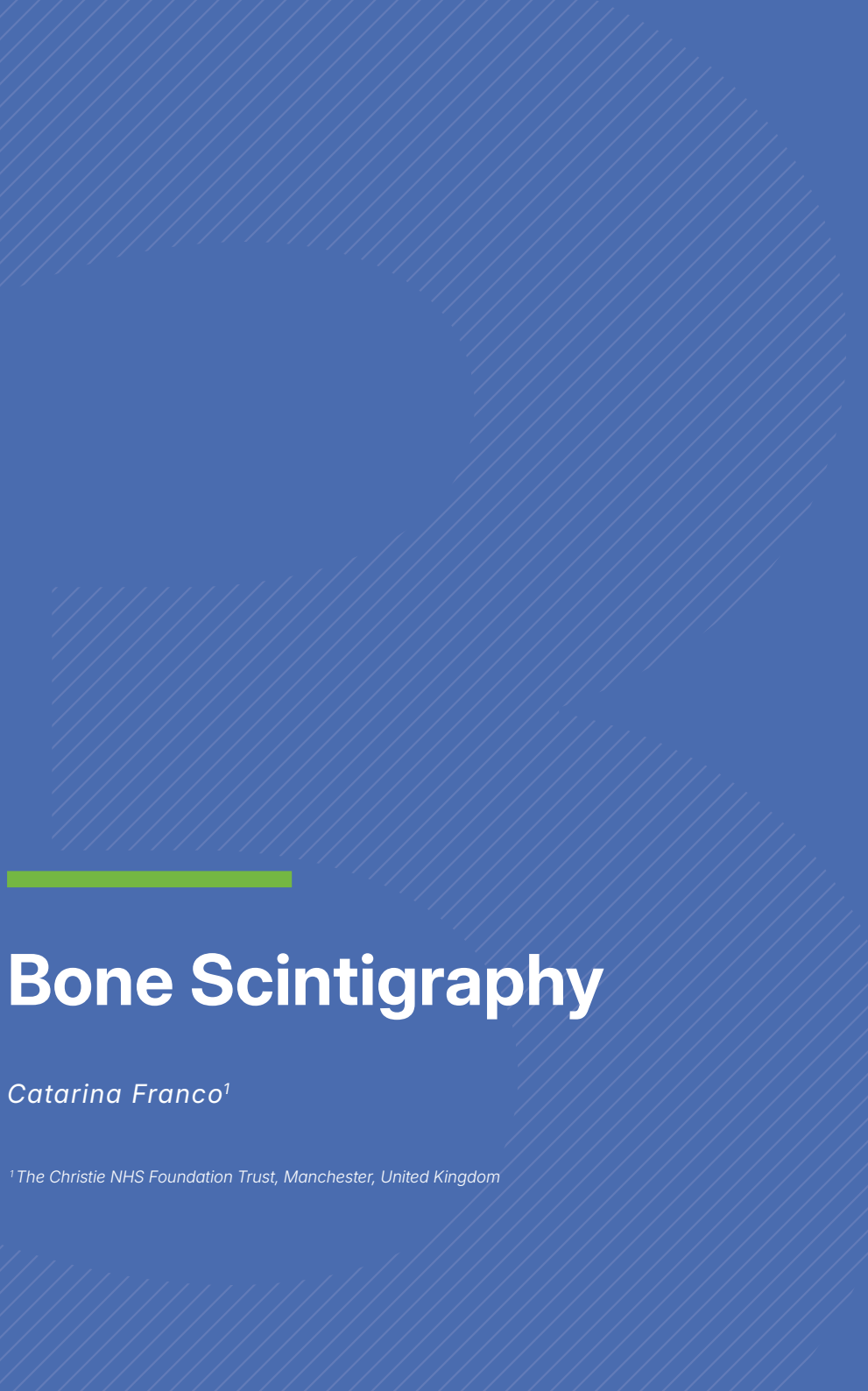
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Bone Scintigraphy

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EXECUTIVE SUMMARY

The purpose of this chapter is to provide support for the nuclear medicine technologist in performing a good quality bone scan, including a 3-phase bone scan in paediatric patients. Paediatric bone scintigraphy is a sensitive examination which enables assessment of a variety of skeletal conditions. To obtain the best outcome, it is important to have a child-centred approach. For many paediatric patients, having a nuclear medicine examination can be a very unfamiliar and scary experience. Having age-appropriate communication, keeping family involved and finding strategies to reduce anxiety in the child are the first steps to creating a safe and pleasant environment for the patient as well as a good way of ensuring a high-quality scan.

Keywords: Bone scan; Paediatrics; ^{99m}Tc -labelled diphosphonates; Child abuse.

INTRODUCTION

Bone scan is an imaging technique which works by intravenously injecting a radiopharmaceutical that will circulate in the bloodstream and be taken up in regions where there is active bone formation. The radiopharmaceutical used is usually a ^{99m}Tc -labelled diphosphonate. After intravenous injection, it circulates in the bloodstream and is delivered to the bones. The uptake of the radiopharmaceutical depends mainly on blood flow and osteoblastic activity, the

uptake pathway being chemisorption to hydroxyapatite crystals (which are a main component of the bone). The amount of uptake reflects osteoblastic activity and local perfusion, which increase during the process of bone growth or when there are skeletal lesions. The radiopharmaceutical attaches to the mineral matrix of the bone near active osteoblasts. Areas with reduced blood supply or low bone turnover show decreased uptake. This biological behaviour allows bone scintigraphy to reflect bone metabolism and remodelling, making it a highly sensitive technique for detecting bone abnormalities [1,2,3]. Since this scan reflects function and is highly sensitive, it can detect bone lesions before any changes can be seen on a conventional x-ray image [1,2,3].

Since the development of ^{99m}Tc -labelled diphosphonates, this scan has become accepted in paediatrics due to its ability to investigate the entire skeleton in a single picture [1, 2].

Although this type of scan is very sensitive, it is not specific. Increased tracer avidity in bones is non-specific and may represent a variety of osteoblastic activities, including inflammatory, neoplastic, or regenerative processes. On the other hand, a bone scan can be used when there is suspicion of a bone lesion, for example. Figures 1 and 2 [4] below show a normal paediatric bone scan in a 6-year-old and a 12-year-old.

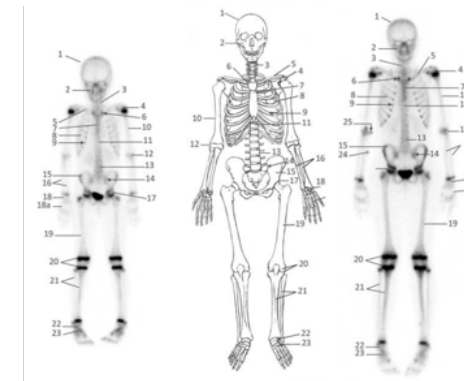


Figure 1. Schematic presentation of the human skeleton, anterior whole-body bone scan images acquired in 6- and 12-year-old children [19]. 1. Skull 10. Humerus 19. Femur 2. Facial bones 11. Thoracic spine 20. Knee metaphyses and epiphyses 3. Cervical spine 12. Elbow 21. Tibia and fibula 4. Shoulder 13. Lumbar spine 22. Ankle 5. Clavicle 14. Sacroiliac joint 23. Foot 6. Sternoclavicular joint 15. Pelvis 24. Injection site 7. Sternum 16. Radius and ulna 25. Lymph node accumulation 8. Ribs 17. Hip 9. Costochondral joints 18. Wrist 18a. Hand [4].

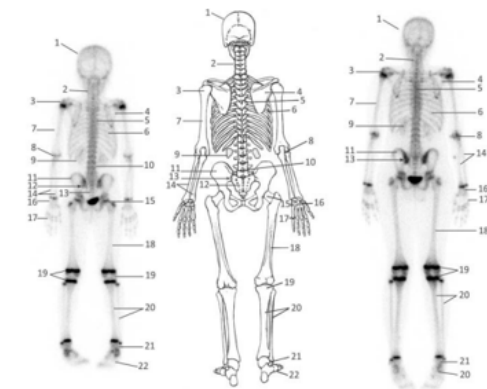


Figure 2. Schematic presentation of the human skeleton, posterior whole-body bone scan images acquired in 6- and 12-year-old children [19]. 1. Skull 9. Kidney 17. Hand 2. Cervical spine 10. Lumbar spine 18. Femur 3. Shoulder 11. Pelvis, iliac bone 19. Knee metaphyses and epiphyses 4. Scapula 12. Sacroiliac joint 20. Tibia and fibula 5. Thoracic spine 13. Sacrum 21. Ankle 6. Ribs 14. Radius and ulna 22. Foot 7. Humerus 15. Hip 8. Elbow 16. Wrist [4].

CLINICAL INDICATIONS:

Some of the most common clinical indications for paediatrics are [1,2]:

- » Infection or inflammation
- » Malignant bone tumours and bone metastases
- » Traumatic bone disease: accidental, non-accidental (child abuse), physical stress- related, bone viability after trauma
- » Bone pain of unknown origin, including extremity pain with non-localising symptoms
- » Aseptic necrosis

CONTRAINDICATIONS

Although pregnancy is uncommon in the paediatric age group, the possibility of pregnancy in female patients of childbearing age should be ruled out. As with any diagnostic procedure performed on an individual when there is a possibility of pregnancy, a clinical judgement is required to weigh the anticipated diagnostic benefit against the potential risks, according to departmental guidelines. Most departments perform a pregnancy check from the age of 12 [1, 2].

PATIENT PREPARATION AND AFTERCARE

Having a play specialist available can be very valuable. By engaging families prior to the procedure, they implement tailored coping strategies that foster cooperation and significantly reduce patient anxiety throughout the procedure. In the case of very young children, it is enough to practise sleep deprivation for a few hours, with feeding immediately before the study

to make these patients calmer and more stable. In older children, on the other hand, the parents being present in the room is essential to increase cooperation. The use of digital tablets, games, and other distraction techniques often allows good quality imaging without using sedation [5, 6, 7].

The scan should be thoroughly explained to the patient and their parents/guardian by the technologist: the patient should be encouraged to drink plenty of fluids after the injection and before the scan, as this is essential to optimise the study and facilitate clearance of the radiopharmaceutical, as well as to minimise radiation exposure. The length of the scan should also be explained, as well as the time gap between injection and imaging. Ideally, with patients that have known issues (such as autism, learning and physical disabilities), it is advised that they visit the Nuclear Medicine department beforehand with their parents or guardian in order to have further discussions with the staff [1,2,3,6,7].

It is also important to ensure that proper and suitable immobilisation tools are available, such as the correct-sized head stabiliser and straps: if the latter is the wrong size, it will not fit the patient, and will therefore not work correctly [1,2,5,6].

Relevant information should be gathered from the parents/child, such as [1,2]:

1. Any bone pain, is the child limping?
2. History of tenderness, swelling, fractures, traumas or other bone lesions
3. Is the patient involved in any form of physical activity?
4. Has the child undergone any surgeries? Radiotherapy or chemotherapy?
5. Presence of metal implants

6. Has the patient undergone this scan before?
7. Check any previous relevant imaging

RADIOPHARMACEUTICAL

In bone scintigraphy, the most commonly used radiopharmaceuticals are bone-seeking agents that accumulate in areas of increased bone activity. The injected activity should be adjusted according to the patient's weight [1, 8].

The most widely used radiopharmaceuticals are ^{99m}Tc -labelled diphosphonates:

- » [^{99m}Tc]Tc-methylene diphosphonate (MDP)
- » [^{99m}Tc]Tc-hydroxymethylene diphosphonate (HDP)
- » [^{99m}Tc]Tc-diphosphonate (DPD)

All these radiopharmaceuticals are safe and effective for use in paediatric bone scans. There is practically no clinically significant difference between them when it comes to diagnostic value. The department's choice will depend on local availability, i.e. which tracer is more consistently available ([^{99m}Tc]Tc-DPD is more common in Europe, for example, but in the US [^{99m}Tc]Tc-MDP is more predominant).

ACTIVITY AND VOLUME ADMINISTERED

The recommended activity to inject for bone scintigraphy imaging can be found on the EANM paediatric dosage card (version 5.7.2016) (Table 1) and in other EANM guidelines [1,8,9].

Dosage Card (Version 5.7.2016)
Multiple of Baseline Activity

Weight kg	Class A	Class B	Class C	Weight kg	Class A	Class B	Class C
3	1	1	1	32	3.77	7.29	14.00
4	1.12	1.14	1.33	34	3.88	7.72	15.00
6	1.47	1.71	2.00	36	4.00	8.00	16.00
8	1.71	2.14	3.00	38	4.18	8.43	17.00
10	1.94	2.71	3.67	40	4.29	8.86	18.00
12	2.18	3.14	4.67	42	4.41	9.14	19.00
14	2.35	3.57	5.67	44	4.53	9.57	20.00
16	2.53	4.00	6.33	46	4.65	10.00	21.00
18	2.71	4.43	7.33	48	4.77	10.29	22.00
20	2.88	4.86	8.33	50	4.88	10.71	23.00
22	3.06	5.29	9.33	52-54	5.00	11.29	24.67
24	3.18	5.71	10.00	56-58	5.24	12.00	26.67
26	3.35	6.14	11.00	60-62	5.47	12.71	28.67
28	3.47	6.43	12.00	64-66	5.65	13.43	31.00
30	3.65	6.86	13.00	68	5.77	14.00	32.33

$$A[\text{MBq}]_{\text{Administered}} = \text{Baseline Activity} \times \text{Multiple}$$

Table 1. Recommended administered activities for [^{99m}Tc]Tc-MDP based on the 2016 EANM Paediatric Card' [1,8,9].
'An update of the EANM Paediatric Card is under preparation. For further information, please check the following website: <https://eanm.org/publications/useful-resources/paediatric-dosage-calculator/>

There is no standard injection volume for a paediatric bone scan. This depends on the cold kit radiopharmaceutical preparation used (activity of ^{99m}Tc -labelled radiopharmaceutical in the kit and concentration in the vial) and is therefore different in each department.

Radiopharmaceutical	Class	Baseline activity (for calculation purposes only) (MBq)	Minimum recommended activity (MBq)
^{99m} Tc-MDP	B	35.0	40

Table 2. Recommended minimum administered activity for [^{99m}Tc]Tc-MDP based on the 2016 EANM dosage card [8,9].

INJECTION TECHNIQUE

In some departments, the patient first attends the Paediatric ward to have the cannula inserted and is then sent to the Nuclear Medicine department to have the intravenous injection. In that case, the cannula should be flushed with saline solution to check if the access is working. Alternatively, in Nuclear Medicine departments that perform paediatric cannulation themselves, maintaining a sufficient team of staff specifically trained in paediatric cannulation is essential [6,7].

Local anaesthetic cream (e.g. EMLA) can be used prior to venepuncture to reduce discomfort (can be applied 1 hour before accessing the vein). During this procedure, in the case of a very young patient, the child can sit down on a parent's lap. For older children, it helps to talk them through the steps of the procedure and to remind them how important it is to keep their arm perfectly still. The promise of a gift, sticker or bravery certificate is another useful incentive. Additionally, the technologist can role-play the injection procedure with one of the parents to gain the patient's confidence [6,7,10].

The decision to sedate a child should be determined on a case-by-case basis. The various technological advances through the years have allowed faster scanning and a high number of efficient studies that require lower radiation exposure. The need

for sedation has thus reduced considerably [6,12,10,11], especially when good distraction techniques are used.

IMAGING PROTOCOL AND IMAGING PROCESSING

When performing nuclear medicine examinations in children, there are many factors to consider when choosing the appropriate investigation, such as the balance of risk and benefits, the level of invasiveness of the procedure, and radiation exposure [12,13,14].

Multiphase bone scintigraphy is divided into three parts: blood-flow images, blood-pool images, and delayed images (Table 3). Blood-flow images are a dynamic acquisition of planar images over the area of interest, the radiopharmaceutical being injected at the same time as the acquisition starts. Blood-pool images include static views taken right after the flow phase, typically within 10 minutes of radiopharmaceutical injection, and visualise the tracer as it diffuses into the extravascular space, highlighting areas of inflammation or increased vascularity [3,14,17].

Delayed bone images are typically acquired 2–3 hours after the radiopharmaceutical injection [6]. This ensures that the active osteoblasts have taken up the radiopharmaceutical while the soft tissue activity has been excreted by the kidneys. Before starting the scan,

the bladder should be emptied: in young children this can be encouraged by the sound of running water or by holding the child upright. For patients that are not toilet trained, parents should bring a spare nappy with them in order to change it before the scan. The patient should be positioned comfortably, using specific paediatric immobilisation devices (such as vacuum mattresses or sandbags) if necessary to minimise motion during the scan. It is important to note that these devices should be used carefully to avoid any risk of airway obstruction and prevent any asymmetrical positioning. For neonates and infants, scheduling scans during natural sleep cycles and utilising “feed and wrap” techniques optimises results. For older children, distractions such as movies or storytelling improve cooperation [15]. In very

young patients, the areas of clinical interest should be acquired first as the child may become less cooperative at a later stage [1].

IMAGE ACQUISITION

A dual-headed gamma camera with a low-energy, high-resolution (LEHR) collimator is frequently used, with an energy window centred on the 140 KeV photopeak of ^{99m}Tc [1][11].

A pinhole collimator can be used if high-resolution images are needed for a very specific small structure [1].

A SPECT/CT (Table 3) can be performed when assessing for infections, suspected osteomyelitis and spondylodiscitis, trauma or stress injury, an unclear origin of bone pain, and finally, in oncology cases, to obtain a more accurate location of a lesion and better specificity. Given the additional

	Views	Matrix	Zoom	Duration
Whole-body scan	Anterior and then posterior	Typically 256×1024	1.0–1.5 depending on child size	20–40 min depending on scan speed
Statics	Anterior, posterior, obliques or laterals	128×128 or 256×256	1.0–2.0 adjusted to the area of interest	5–10 min per spot depending on counts
Blood flow	Anterior and posterior of the area of interest	64×64 or 128×128	Typically 1.5–2.0	Typically 2 min
Blood pool	Anterior and posterior of the area of interest	128×128 or 256×256	Typically 1.5–2.0	Typically 3–5 min
SPECT/CT	SPECT area of interest	128×128	None	120 views 20 sec/view

Table 3. Gamma[te1.1][LM1.2][VT1.3][te1.4] camera acquisition parameters [11].

radiation exposure to the patient, whether or not to perform CT should be carefully considered based on the patient's age and should be strictly limited to the area of interest [14,15]. When performing SPECT/CT in children, a prior consultation with a medical physicist is important in order to optimise the low-dose paediatric CT protocols. Where appropriate, it is recommended to do all the imaging with the child in the supine position [14,15].

After imaging, a quality assessment should be performed on the acquired raw data, specifically assessing for movement. If there is any, additional images should be acquired as needed; however, in the case of SPECT/CT, a repeat CT should be avoided due to the radiation exposure. In cases where spot views were performed, they should be merged into whole-body with sides clearly labelled while adjusting scale and intensity to clearly distinguish the normal areas of uptake from those with increased radiotracer activity. The injection site or any artifacts that are very noticeable on the images should also be labelled [14,15].

IMAGE INTERPRETATION

Osteoblastic activity is a common response to various pathologies, therefore when an abnormal uptake is detected, it should not immediately be associated with a specific lesion. It is necessary to analyse the normal pattern of the radiopharmaceutical uptake, such as multiple random foci in metastatic disease, or a pattern of aligned spots of rib uptake in trauma. Correlation with other imaging modalities such as x-ray, CT and MRI improves accuracy by helping to clarify findings and better assess complex or small lesions [11].

The paediatric skeleton is in a constant state of growth and maturation from birth to adulthood. Studies can often be challenging to assess due to difficulties related to epiphyseal plate activity interpretation [11]. In a skeleton undergoing development, the rapidly growing areas look different at different stages of maturation. In the early years of paediatric bone scintigraphy, it was observed that the appearance of the physes in the first year of life differs from that in a more mature child [4]. When assessing a paediatric bone scan, it is important to understand the age-dependent physiological and anatomical changes. The patterns of radiopharmaceutical uptake will differ depending on skeletal growth as well as on metabolic activity, which will vary across the various stages of skeletal development. Recognising these normal variations is essential in order to be able to identify a real pathology [1].

There are a few potential interpretation errors that may be caused by:

- » Urine contamination
- » Injection site, prosthetic implants
- » Attenuating artifacts that might mask the normal structures
- » Patient movement

CLINICAL CASE 1

- » 11-month-old child
- » Weight of 1780 g with a premature birth age of 34 weeks, was in intensive care for seizure attack, aspiration pneumonia, and subdural and subarachnoid haemorrhage.
- » Developed progressive lower limb swelling and his left elbow showed skeletal malformation following a fall

» Bone scan was performed for an evaluation of suspicious malunion fracture, bone infection or pre-existing medical conditions, because metabolic disorders and bone diseases may make a child's bones more vulnerable to fracture

Multiple areas of uptake throughout the whole body (Figure 3) were found, which suggested child abuse. A series of x-rays demonstrated calvarial fracture lines at the left temporoparietal region, bony anomaly of the spine, multiple old fractures with callus formation involving posterior aspect of left 10th, 11th ribs, right proximal humerus,

bilateral proximal femurs, and metaphyses of tibias (Figure 4).

MRI was performed and showed metaphyseal fractures of distal left femur and proximal bilateral tibias with extensive periosteal haemorrhage, which also indicates child abuse.

The initial and follow-up evaluations for non-accidental injury (NAI), as shown in Figure 5, typically rely on skeletal surveys [17,18]. A bone scan delivers a higher effective dose than a skeletal survey [18]; however, it helps to confirm occult bone lesions [19,20] and increases the

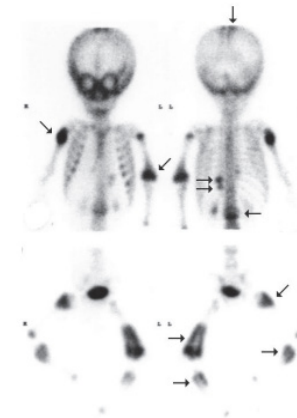


Figure 3. Bone scan: multiple increased radioactive foci throughout the whole body (arrows) were found by accident [16].

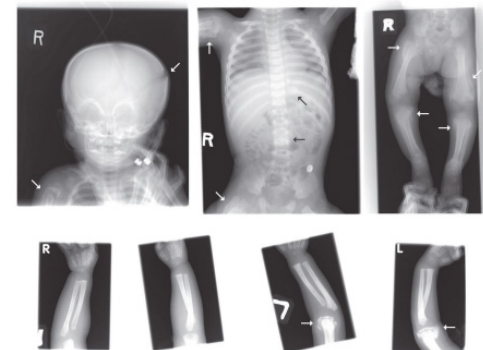


Figure 4. Series of x-ray images [16]. MRI was performed and showed metaphyseal fractures of distal left femur and proximal bilateral tibias with extensive periosteal haemorrhage, which also indicates child abuse.

confidence in interpretation with which radiologists diagnose or exclude injury [18].

CHILD ABUSE

Physical abuse in infants can cause severe and lifelong harm. For this reason,

imaging is crucial when abuse is suspected. The advantages include assessment of injuries that need treatment, but it can also reveal prior lesions that could have been missed and may point to a history of ongoing neglect [19,21,22]. These findings

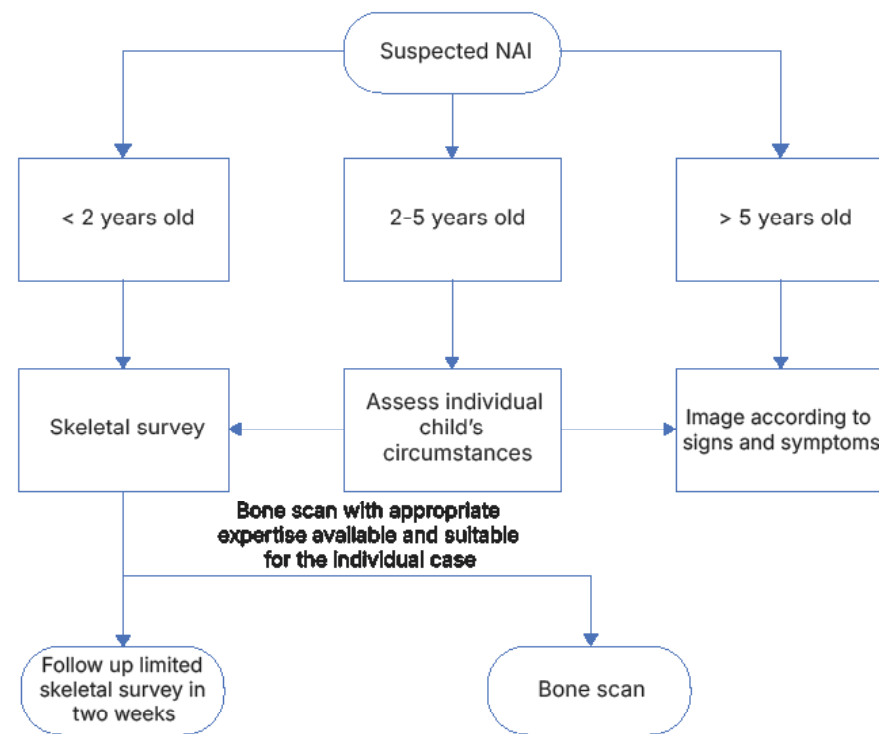


Figure 5. Flow diagram of recommended imaging pathway [18].

play a very important role when it comes to decision-making by child protection authorities and legal proceedings [19,21].

Non-accidental injury (NAI) happens quite often, with over 46,000 children in the UK on the child protection register. It is estimated that one in four young adults have been severely maltreated during childhood [23]. The Royal College of Radiologists and the Royal College of Paediatrics and Child Health advise the use of skeletal survey (SS) as the first choice for imaging investigation for NAI in children up to 2 years old, due to evidence of the high number of detected fractures in this age group [23] [24].

A bone scan offers a high-sensitivity exam that complements the traditional skeletal survey. It allows the diagnosis of more subtle fractures that would not be evident in x-rays [25,26]. Even though a bone scan can be used as a complementary technique to investigate NAI, there is very little recent literature focusing on this. Guidelines advise the use of a bone scan when it is not possible to perform a follow-up SS [23,25].

Clinical Case 2

» An 11-year-old boy complained of severe right thigh pain after a passenger car accident

» A plain x-ray taken revealed a fracture of the right femoral shaft

» Closed reduction and internal fixation were performed using intramedullary titanium elastic nails. Six months after the operation, bone union was achieved and the nails were removed

» Nine months after nail removal, the right leg was unexpectedly noticed to be 5 mm shorter than the left one

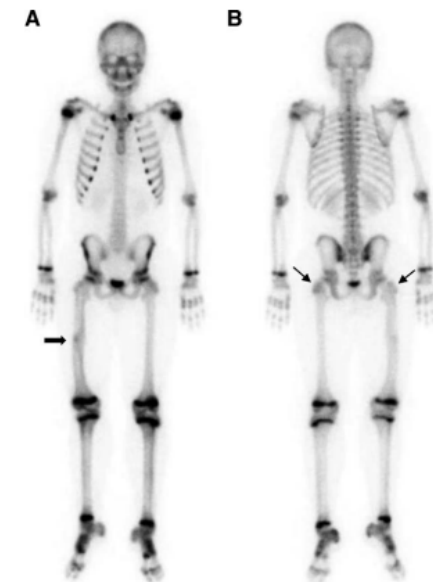


Figure 6. Whole-body bone scan at 9 months after nail removal [27].

» A bone scan was performed to assess growth plate activity of the femurs

» On the anterior view, increased uptake is observed at the previous fracture site in the right femur (Fig. 6A) [27]

» On the posterior view, the radioactivity of the growth plate in the right greater trochanter appeared lower compared to that of left femur (Fig. 6B) [27]

» SPECT/CT revealed that the uptake of the growth plate in the right proximal femur was much lower than that in the left femur, suggesting a further increase of leg-length discrepancy

Notes for technologists

Key behaviours that may be indications of neglect can include non-engagement on the part of parents or carers, past incidents, mental health problems, a parent's substance misuse, and carers who experienced abuse themselves, which consequently affects their own parenting [28, 29, 30]. It is crucial, as a professional responsibility, to alert the Lead Technologist and Lead Physician to any concerns so that safeguarding risks are addressed.

When dealing with paediatric patients, it is important to use communication methods that best suit the child, such as drawings, books, activities or interpreters. In cases of suspected child abuse, communication should be clear; the technologist should listen actively, be open to questions, and ascertain that the carers and patients understand. In all paediatric interactions, respect must be shown for cultural diversity and religious beliefs; breaks should be allowed whenever needed, and team members should ensure that information

is provided in a comfortable and private setting [21, 28, 29].

CONCLUSION

Developments in hybrid imaging such as SPECT/CT have improved the interpretation accuracy of bone scans [30], providing greater anatomical information, spatial resolution and sensitivity. Bone scintigraphy is a valuable tool for assessing a range of clinical indications, including suspected child abuse, as it detects fractures in places that might be difficult to assess with traditional x-rays [3, 18]. It shows early pathophysiological changes and soft tissue lesions and reduces misinterpretation of normal growing features [23].

It is important to underline that a child is not a smaller version of an adult, so the technologist needs to provide the right care and attention to try and meet the patient's specific needs. Involving other members of staff, such as a play therapist, can greatly improve the child's experience and make the whole procedure easier, quicker and more efficient. Additionally, allowing for a longer time slot when performing paediatric nuclear medicine procedures is highly advised as it can reduce levels of stress anxiety for both the child and their parents.

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Renal Scintigraphy – Dynamic Renogram and Static Renal Scintigraphy

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EXECUTIVE SUMMARY

Renal scintigraphy studies are performed in nuclear medicine to provide physiological and functional information about the renal system. Dynamic Renography is used to assess perfusion and drainage of the renal system, most commonly with the radiopharmaceutical [^{99m}Tc]Tc-MAG3, whereas Static Renal Scintigraphy uses [^{99m}Tc]Tc-DMSA to assess the total and split renal function.

In paediatrics, renal studies can be challenging and require a high level of enthusiasm, organisation and skill from staff to complete them successfully. Successful completion can be extremely rewarding for technologists and patients.

Departments are advised to ensure adequate training and support is available for staff when undertaking these studies for paediatric patients, until confidence is gained. Additionally, an awareness of the needs of both neurotypical and neurodiverse paediatric patients of all ages is essential to make the study accessible for all and ensure that patients and caregivers have a positive experience in department.

This guide aims to give technologists the information they need to successfully complete renal scintigraphy studies in the paediatric population.

Key words: Paediatric; renogram; dynamic; neurodiverse; neurotypical; immobilisation

INTRODUCTION

Paediatric renal imaging in nuclear medicine encompasses two main studies: dynamic renography (DR) and static renal scintigraphy (SS). In DR, [^{99m}Tc]Tc-mercaptoacetyl-triglycine ([^{99m}Tc]Tc-MAG3) is used to assess perfusion and clearance

of the renal system, whereas in SS, [^{99m}Tc]Tc-dimercaptosuccinic acid ([^{99m}Tc]Tc-DMSA) is the radiopharmaceutical of choice to assess differential renal function. Both studies can be challenging to perform on the paediatric patient, whose degree of understanding, maturity, and emotional intelligence will vary not just with age, but also between children of the same age [1].

This chapter aims to give technologists both technical and practical guidance on completing renal studies successfully in paediatric patients.

HISTORY AND PRINCIPLE OF RENOGRAPHY

Nuclear medicine was first used for renal imaging in paediatric patients in the early 1960s [2]. Each kidney was imaged separately, as the gamma camera field of view (FOV) was only 28cm [2]. Later in the 1960s gamma camera technology evolved, resulting in a 48cm FOV. This meant that simultaneous imaging of both kidneys could be performed on the paediatric patient, which was especially useful for dynamic renal studies [2].

Since then, all aspects of nuclear medicine have continued to evolve, and renal scintigraphy remains an important diagnostic tool in paediatric patients with urological symptoms [3], the aim being to provide key information regarding physiology and function of the kidneys.

This guide aims to give technologists confidence and a good understanding of renal scintigraphy studies in paediatrics.

Pathology

There are many causes of urinary tract abnormality in paediatric patients, for which DR and SS provide essential diagnostic information for patient management [3].

Patients will often be referred for scans after or in conjunction with an ultrasound scan (US) [4]. US is used to provide anatomical information regarding urinary tract abnormality, whereas nuclear medicine provides functional information [4].

The literature shows that patients are increasingly being referred after abnormal findings on pre-natal US, where congenital conditions such as hydronephrosis or hydroureteronephrosis can be visualised [4,6]. In other cases, children are referred for the investigation after frequent urinary tract infection (UTI), abdominal mass or the presence of renal calculi [3, 5].

SS is the gold standard examination for assessment of total and split renal parenchymal function and is also used for the detection of scarring after UTI [5, 7].

Clinical Indications for Dynamic Renography

Common clinical indications include: assessment of vesicoureteric reflux, non-obstructive dilatation, acute or non-acute ureteropelvic junction obstruction, assessment of hydronephrosis or hydroureteronephrosis, assessment of renal system drainage, bladder dysfunction, renal transplant assessment, interval scanning to see progression of renal function, evaluation of function and drainage post-surgery, recurrent abdominal pain assessment and assessment of renal function post-trauma [3,4,7].

Contraindications

Absolute contraindications to DR are rare [1,8].

Relative contraindications to DR may include the following, however clinical judgement should be used and physician advice sought where required before cancelling any examination:

Full bladder in potty-trained children, required for the following reasons:

- » Risk of delayed drainage from upper urinary tract due to intravesical pressure
- » Likelihood of premature end to the study

Non-compliance of the procedure due to the detrimental effects of motion [8].

Patient not adequately hydrated [4, 9] (see patient preparation and aftercare section for further information).

Allergy to furosemide if protocolled for use [1, 8].

Clinical Indications for Static Renal Scintigraphy

Common clinical indications include: assessment of total/split renal function, assessment of scarring post UTI (imaging must be performed 4–6 months post UTI), renal transplant assessment, assessment of horseshoe, solitary, ectopic, pelvic or duplex kidney, assessment of congenital and acquired renal abnormalities [5, 7].

Contraindications

In paediatrics, renal scintigraphy is generally safe, and true contraindications are uncommon. Most concerns relate to patient clinical stability, radiation exposure, and proper patient preparation.

PATIENT PREPARATION AND AFTERCARE

Pre-appointment

It is advisable to book longer appointment slots for paediatric patients – Administration of Radioactive Substances Advisory Committee (ARSAC) notes for guidance recommend increasing slot time by 50% [9,10]. This can be clinically challenging, but increasing the time is essential for both staff and patients to ensure a patient-centred approach is maintained, limiting stress and increasing the chance of a successful examination. Some departments may book paediatric-specific lists. Although this can be beneficial, the increased wait times for patients later in the day can lead to increased anxiety. Departmental logistics also need to be considered, to ensure that paediatric patients in an adult and paediatric mixed list can wait for delayed imaging away from adult patients who are likely to have had a much higher radiation dose administered.

It is recommended that at least one member of staff is experienced in the scanning and administration of paediatric patients to ensure smooth running of the examination, increasing the chance of patient compliance [1,9,10]. Ideally two staff members must be available for the examination to run smoothly [9].

It is impossible to overstate the importance of sending out a detailed information leaflet to the patient's caregiver prior to this examination [1, 3, 10]. This is because a detailed information leaflet allows caregivers to plan, make provisions and prepare the child for the test ahead of the day.

The leaflet should give a basic explanation of what will happen on the

day and how long patients will be in department [1,3]. For DR studies, it should also provide hydration instructions. It should include a brief explanation of radiation safety requirements and associated post-procedure advice [4, 12]. This ensures that the parents can give full informed consent for the radiation exposure of the child prior to the examination, without coercion [12]. Any instructions provided must clearly detail radiation advice in the case of a pregnant mother attending the examination with the patient [1].

It is helpful to request that the caregiver bring extra nappies and a change of clothes in case of accidents. In addition, department contact details should be included so that caregivers are given the opportunity to discuss any further requirements ahead of the appointment.

Neurodiverse patients

According to the UK National Institute of Health, the term neurodiverse refers to people that experience different ways of learning, feeling, thinking and behaving with their surroundings [13]. Examples of neurodiversity include neurological developmental disorders such as Attention-Deficit Hyperactivity Disorder (ADHD), dyslexia and autism spectrum disorders; this list is not exhaustive, however, and the term neurodivergence applies to any person that falls under the above definition. Although numbers of patients with neurodivergence are difficult to quantify, they are thought to be rising [14]. In 2021, the World Health Organisation estimated that 1 in 127 people on a global scale were autistic, though this figure is not specific to paediatric patients [15]. Patients that fall into the neurodiverse category often have co-morbidities and thus

commonly require medical investigations, which is why a good understanding of these patients is key to success in the Nuclear Medicine department [14, 16].

Paediatric patients in general can be challenging to diagnose due to their differing levels of understanding and communication [10, 17]. In addition to these challenges, neurodiverse paediatric patients often have different experiences of sensation, meaning that their communication of symptoms and feelings may be more challenging to interpret when compared to that of a neurotypical child [16,17]. If not managed effectively, these differences can lead to patients having negative experiences in the hospital environment [16]. Environmental factors such as bright lights and loud noises can exacerbate illness and lead to overstimulation, potentially causing non-compliance during the study [16]. In addition, patients may have had previous negative experiences in hospital, leading to more extreme reactions to elements of the study that would not be expected in a neurotypical patient.

As such, technologists must be able to adapt to the patient's individual needs without prejudice. Where possible, departments should encourage staff to educate themselves about or provide training regarding neurodiverse patients, to enhance understanding of the different conditions that fall under this umbrella term [17].

Simple measures such as reducing stimuli in the department, including lowering of lights and ensuring clear explanations are provided in a calming peaceful area, can improve the experience for these patients [10,18]. In addition, allowing extra time for examinations will give these patients time to adjust to the clinical environment [17].

For all paediatric patients, departments can encourage parents to bring the patient's comfort toy and/or favourite personal devices with programmes or games for distraction. If this is not possible, toys or books can be provided to distract patients [10,17]. Essentially, whatever resources departments have access to, technologists should ensure that they follow a patient-centred approach that caters to the needs of neuro-typical and neurodivergent patients.

Preparation on the day – explanation and checks

The technologist's first and most important job is to make the patient and parents feel welcome and relaxed in the department [1,10]. If this can be achieved, the paediatric patient is more likely to be compliant with the procedure. It helps to have two staff members available for the procedure to manage all parties and steps [9,10].

It is essential to check the patient's clinical indications and cross-reference this with the parents to ensure that the examination is justified [3,12]. For example, if the scan is required post stent insertion, confirmation should be sought to ensure that this has been done before proceeding. It should also be checked that the request has been vetted and justified by the nuclear medicine practitioner to ensure that it is fine to proceed with the examination.

Regular medications can continue, unless instructed otherwise by the nuclear medicine physician.

Full explanation of the procedure should then be given to the caregivers and the patient, detailing what will happen, how long it will take and relevant radiation protection information.

Preparation on the day – explanation and checks required for Static Renal Scintigraphy

If the patient has been referred for imaging post UTI, the technologist needs to ensure that the last episode was 4–6 months previously [7]. This is because scarring caused by UTI within 4–6 months may resolve after this time. However, if indicated, SS can also be used to confirm a diagnosis of acute pyelonephritis and has a sensitivity of over 90% [7].

Patients with congenital abnormalities often require extra imaging, therefore it is advantageous to discuss this with parents prior to the start of the examination.

Preparation on the day – explanation and checks required for Dynamic Renography

If a diuretic is given as part of the protocol, the side effects of this should be explained (see aftercare). Ideally patients should be orally hydrated prior to arrival in the department. Infants can continue to be bottle or breastfed. If this has not been done, patients should be given oral hydration prior to commencement of the procedure [3,9,19]. Good oral hydration is essential prior to the scan. This is because:

1. More concentrated urine will have a higher concentration of tracer, which can prevent visualisation of the bladder during the dynamic phase of the study. This can be misleading in results as the collecting system can appear obstructed due to the appearance of delayed drainage curves [9,19].

2. Dehydration can prevent the diuretic from working properly [1, 19].

3. The administration of a diuretic can cause dehydration, therefore inadequately hydrated patients are more likely to suffer side effects from this, such as syncope [4].

If venepuncture is done in the department, anaesthetic (numbing) cream can be applied whilst the patient hydrates, as this needs time to take effect (approx. 45–60mins) [3, 20].

If there is any doubt about the ability of the patient to tolerate the scan, the patient should be shown the room and a practice run of being in the immobiliser or on the scanning couch can be performed to ensure that the procedure is possible prior to radioactive injection. Sedation is not routinely offered for this scan as it is unnecessary, can delay the production of urine and cause dehydration, affecting the results of the scan [3,19]. Some centres may be able to book a play specialist for children who struggle to tolerate the length of the study [11]. These professionals are often invaluable in helping staff calm a distressed child, and should certainly be utilised where possible.

Toilet-trained children should be asked to void prior to the scan, as a full bladder can delay emptying [1, 8, 19]. Children in nappies should have a fresh nappy put on prior to the scan [1]. The reason for this is two-fold: firstly, this ensures the child starts with a fresh clean nappy, which increases their level of comfort; secondly, a full nappy is more likely to leak urine. The contamination from this can affect image quality if the leak is absorbed into the clothing up the child's back, masking the ureters, bladder and kidneys. The contamination can also put the department's baby-immobilising devices or scan bed 'out of action' if severe, which can render it useless for immobilisation of the current and subsequent patients. Because of the

risk of contamination from leaky nappies, it is recommended that departments ensure they line any immobilisation devices and/or the scanning couch with absorbent pads and available linens for these studies.

Preparation on the day – venepuncture

Paediatric patients must be cannulated by staff appropriately trained in paediatric venepuncture techniques. The type of venepuncture used for each study will vary depending on the departmental protocol.

Anaesthetic (numbing) cream should be applied to the patient 45–60 minutes prior to cannulation. This should be applied to more than one area in case of failure to cannulate the child in the first instance.

In DR studies where a diuretic is given shortly after the tracer bolus injection, a butterfly needle may be appropriate. However, in departments where the diuretic is given at 15 minutes post-injection, and especially for very young children, the use of a cannula is recommended due to the risk of the butterfly needle being dislodged [1]. Care should be taken to flush the cannula prior to injection of tracer, to ensure patency and reduce the risk of extravasation [3, 9].

Distraction techniques should always be used to make the patient feel as comfortable as possible during cannulation. It can be beneficial to block the patient's view of the needle insertion with the aid of a book or toy. Alternatively, younger children can be cuddled on a parent's lap, with the limb that will be used for cannulation placed around the parent's back. Regardless of the method used, the technologist should ensure patients are comfortable before starting. Good communication is essential to build rapport and ensure both parent and child understand what is happening and when.

Some sites have access to additional equipment to assist in the cannulation of paediatric patients. A near-infrared vein visualisation tool can be especially helpful, as this provides a visual map of the patient's vasculature (see Figure 1). The use of ultrasound for cannulation is also a valuable tool. Some sites can get children cannulated by their local children's venepuncture team ahead of appointment or have anaesthetic/specialist support [1]. This has the added advantage of the patient not associating the Nuclear Medicine department with the discomfort of cannulation.



Figure 1. Demonstration of an infrared vein visualisation tool on a young child, showing the vasculature in their hand (AccuVein AV500) [21]; Image courtesy of AccuVein.

Preparation on the day – immobilisation

Good immobilisation of paediatric patients for renal scintigraphy is essential to limit motion artifact (see Figure 2) [1,3]. The upper age range after which immobilisation becomes unnecessary is difficult to quantify because of the differing levels of understanding and maturity within paediatric age groups. It is recommended that immobilisation is considered even in older patients, due to the negative effects of motion artifact on the study.

Immobilisation should be approached with care and a high level of communication to prepare the patient and parents, as no method is infallible [3]. It should be noted that immobilisation differs from physical restraint, as it should take place with full parental consent and aim to make the child comfortable and still, rather than being physically forced to stay still [1]. It must be emphasised to parents that they can still touch and talk to their child throughout the examination, as this is key to calming the anxious child.

Immobilisation devices should be lined with an absorbent pad and pillowcase or linen sheet. This enables the device to be comfortable, to avoid contamination and to be easily cleaned, as previously discussed.

Some devices make patients very hot, therefore clothing should be assessed prior to immobilisation. Heavy items such as jumpers should be removed. A blanket can then be placed over the top of the device and the child to keep the patient warm, as this is easily removable. Items of clothing with metal fastenings such as zips or poppers over the area of interest should be removed prior to immobilisation. Removal of clothes during the test should be

avoided as the movement will likely render the study non-diagnostic. Care should be taken to ensure the cannula is accessible for the examination, and not over the area of interest. This is because residual activity is often visible at the cannulation site, causing image artifact.

Aftercare

Where possible, patients should be rewarded with a sticker or praise, to ensure the last impression of the department is positive, which may help alleviate fear in future examinations [1, 10].

If a diuretic is administered, caregivers and patients should be counselled on the potential after-effects of furosemide, such as the need to urinate more frequently and more urgently for up to 6 hours [20,23]. Patients may feel dizzy or sick when sitting up after administration [20,23,24]. In such cases, ensure that the patient stays hydrated to counteract these effects.

Advice on radiation protection measures should be given, such as performing frequent nappy changes, encouraging frequent drinking, hand washing, and encouraging frequent urination in toilet-trained children [1]. It can also be advisable to delay bathing until the following day in non-toilet trained patients to prevent bathwater contamination.

Radiopharmaceutical – Dynamic Renography

According to the literature, [^{99m}Tc]Tc-MAG3 is the recommended and most widely used radiopharmaceutical for DR, especially in paediatric patients and those with impaired renal function [24,25]. This is because it is protein-bound within plasma, meaning that it has good renal uptake due to being removed from the plasma through

both tubular excretion (80%) and glomerular filtration (20%) [4, 25-27].

In addition, the image quality using [^{99m}Tc]Tc-MAG3 is superior to that obtained with [^{99m}Tc]Tc-DTPA due to the extraction fraction being 2–3 times higher, resulting in higher-contrast, sharper images because of the improved kidney-to-background ratio [3,6,24,26]. The extraction fraction refers to the percentage of plasma (and bound tracer) that is extracted from the blood by the kidneys in a single pass [27].

Despite this, [^{99m}Tc]Tc-DTPA is a suitable alternative if access to [^{99m}Tc]Tc-MAG3 is limited. It is filtered purely by the glomerulus, meaning that glomerular filtration rate (GFR) can be directly calculated from the study, as it mirrors renal clearance [26]. The extraction fraction is estimated to be 20%, so curves may be noisier than those obtained using [^{99m}Tc]Tc-MAG3 [4, 24, 25, 27].



Figure 2. Examples of infant and child vacuum immobilisation devices used in the author's department. The devices are pictured with permission from Meditech [22].

Radiopharmaceutical – Static Renal Scintigraphy

[^{99m}Tc]Tc-DMSA] is the recommended radiopharmaceutical for SS. 40–60% is absorbed and retained in renal tubules and is thus present in the renal cortex at 2 hrs post injection, then slowly excreted through the urine [5, 27].

Activity and Volume

Paediatric patients are especially vulnerable to the harmful effects of radiation. Activity should therefore be scaled down by bodyweight, in line with the guidance available from the EANM Paediatric Dosage Card version 5.7.2016, to keep activity as low as reasonably practicable [4, 28].

Injection Technique – Radiopharmaceutical

A minimum of two staff members should be present during injection to ensure that it takes place without any radiation incident and that the patient is well supported [9]. The cannula or IV access should be flushed with saline prior to radiopharmaceutical administration to ensure that the line is still patent and to limit the risk of extravasation if it has become dislodged [3,9]. The radiopharmaceutical should be injected as a bolus, followed by a good flush of saline to clear activity from the IV line [25].

For DR studies this will ensure that the first blood pass can be visualised in cases where this is required in the local protocol, and that the resultant time-activity curve represents the real-time kidney perfusion. This is not as clear when poor technique is used and may appear as a delay in perfusion on the images [25, 27].

Imaging Protocol

For DR studies the scan should be started promptly as the tracer is injected. For SS, tracer should be injected and delayed images acquired at 2–4hrs [7].

Prior to both studies:

» Send patient to the toilet to void or change nappy.

» Patient should be supine and immobilised if necessary on scan table.

» Acquire using the posterior detector only unless a horseshoe or ectopic kidney is present, in which case an anterior scan is also needed for differential renal function [4]. The posterior camera should be as close as possible to the scan table to reduce the negative effect of distance on image quality.

» If a dual-headed camera is used, the anterior camera can be moved away from the patient for easy access and comfort [4].

» Check positioning and select appropriate zoom. Where possible, the field of view should include the following:

- Superior – heart (first blood flow – DR only)
- Inferior – symphysis pubis (below bladder)
- Laterally – skin borders

Dynamic Renogram acquisition parameters

The dynamic phase of the renogram will vary in length depending on the child's age. If the child is toilet trained, the study is unlikely to run to the full time, as the effect of the diuretic will make them need

to void more urgently and more often than usual. Staff should be aware that younger children have less awareness of when they need to void and less ability to hold their urine. If the child is in a nappy, the study can continue for as long as they are able to tolerate it, unless the nappy leaks causing contamination which may affect image processing later. In any scenario, it is ideal to get a minimum of 20 minutes total scan time, to adequately assess the filling and drainage of the renal system [9]. Staff should remain vigilant and use good communication skills to gauge when it is appropriate to end the dynamic phase of the study.

Two key protocols exist in the literature for the dynamic phase of the DR, which vary in length depending on the administration time of the diuretic furosemide [4, 25]. The standard recommended dose of furosemide is 1mg/kg up to a maximum dose of 40mg [4]. Further guidance can be found in the EANM Procedural Guidelines for Diuresis Renography in Infants and Children

[4]. Table 1 shows the basic acquisition parameters for both techniques.

Dynamic Renography static acquisition parameters

Static images allow for quantification of drainage. Images should last between 60–120 seconds and be taken at the following intervals [4]:

» Pre-void – Immediately post dynamic and before voiding or voiding study

» Post-void/voiding study – Patient should be upright for a minimum of 10 minutes between these phases, to ensure that gravity has a chance to drain any residual activity from the renal system [4]

» Delayed post-void after a minimum of 60 minutes. Patients should be asked to void prior to this image, or if in nappies the nappy should be changed and the patient walk or remain upright in the interim [6].

Furosemide injection time	20–30 min post tracer [4]	0 min – simultaneous tracer and furosemide [4]
Frame rate	1–2 seconds for 2 min (vascular phase) 10–15 seconds for 5 min (perfusion phase) 20–30 sec for up to 30 min (clearance phase) [25] or 10–15 sec for total of 40–60 min [4]	10–15 seconds [4]
Total scan time	50–60 minutes [4,25]	20 minutes [4]
Matrix	125×125	125×125
Collimator	Low energy high resolution. General purpose or low energy all-purpose [4,25]	Low energy high resolution. General purpose or low energy all-purpose [4,25]

Table 1. Basic acquisition parameters for two Dynamic Renogram protocols [4, 25].

Static Renal Scintigraphy acquisition parameters

Posterior and posterior left/right oblique static images should be acquired as a minimum. For assessment of geometric mean, an anterior static view should be added. This is especially important for assessment of horseshoe and pelvic kidney, where the kidney will overlie bone anatomy on posterior images. Consideration can be given to SPECT image acquisition in these cases [5].

Acquisition time for this study will vary due to patient size and dose. However, scans should be acquired for 300,000–500,000 counts, using a matrix of 128×128 and a low-energy high-resolution or any high/ultra-high resolution parallel-hole collimator [5].

Dynamic Renography Image Processing

Detailed image processing guidelines can be found in the EANM Procedural Guidelines for Diuresis Renography in Infants and Children [4], which are summarised below:

Image processing – dynamic phase

» Differential renal function is generated from the summed dynamic phase images, incorporating each kidney within the region of interest (ROI).

» Ensure to motion correct if needed prior to drawing the ROIs.

» Background ellipse should be placed next to each kidney for subtraction. Ensure this is not over any part of the renal collecting system (particular care should be taken not to include the ureters in this stage), the kidneys or spleen.

» Ensure small region of interest is placed over the heart.

» These ROIs will produce time-activity curves for analysis.

» Mark or annotate time of furosemide administration if not automatically generated.

» Send dynamic cine, time-activity graphs, screen capture showing ROIs and any other images as required by local protocol.

Image processing – static images

» If possible, display all statics on a single page.

» ROI should be drawn on the first image and copied exactly onto all other static views, as required. This is because the retention percentage is calculated on the counts within the region on each image, so it is essential that this is the same on all images.

» The percentage will probably be calculated by the processing software. However, if this is not the case, it can be calculated manually.

Static Renal Scintigraphy Image Processing

» Black-and-white static images should be displayed and sent on one page.

» For calculation of split function, a ROI should be drawn around each kidney with small ellipse at the lateral border of each kidney to exclude BG activity from the final calculations [5]. Departments may have access to software which calculates the split function for them, but if not this can be done manually based on the combined and separate count percentage in each kidney.

Image Interpretation

Clinical Case 1

Presentation: 2-year-old patient presenting with recurrent urinary tract infection and bilateral hydronephrosis. Preliminary bloodwork showed poor renal function. The patient came to Nuclear Medicine for a DR to assess the extent of the hydronephrosis and to see if there was an obstruction in the renal collecting system. Furosemide was administered 15 minutes post radiopharmaceutical injection. An indirect voiding study was also performed to check for reflux.

Results: The patient report showed that there was bilateral hydronephrosis and hydroureters with drainage into an enlarged urinary bladder, but with no obstruction. The voiding study was non-diagnostic due to residual tracer in the dilated kidneys and ureters.

The hydroureters can clearly be seen on the delayed static images (Figure 3).

The lack of obstruction is demonstrated on the time-activity graph, which has two fairly uniform perfusion and clearance curves (Figure 4). The relative function of each kidney is: Left (shown in blue): 39%, Right (shown in red): 61%.

Figure 3

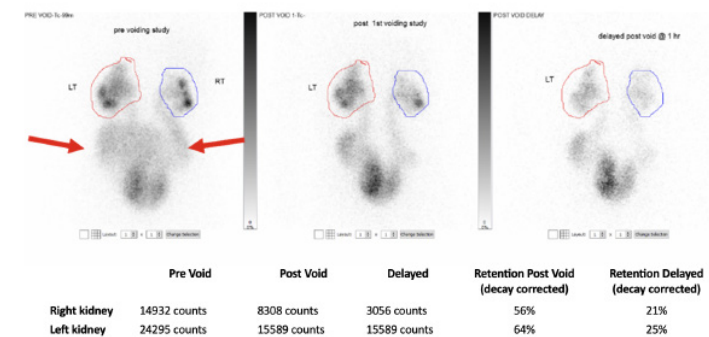


Figure 3. Pre-post and delayed voiding images with hydroureters clearly visible, marked on the images with red arrows. The featured images are reproduced courtesy of Oxford University Hospitals (OUH).

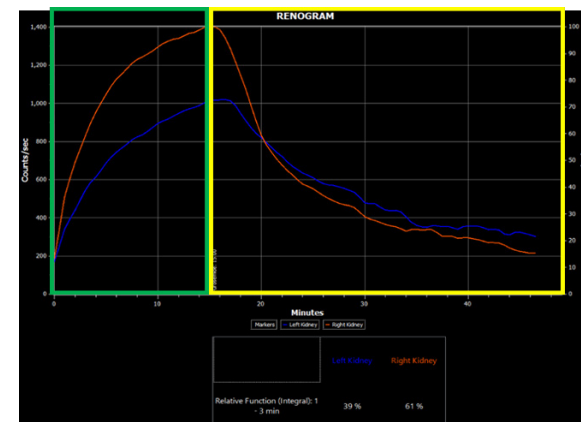


Figure 4. Graph showing perfusion curve in the green box and clearance curves in the yellow box. In this case furosemide was administered at 15 min post-injection, where the vertical lines of both boxes meet. The featured images are reproduced courtesy of Oxford University Hospitals (OUH).

This patient went on to have surgery and was for renal scintigraphy to check for scarring due to suspected ongoing reflux (Figure 5). Results showed stable reduced split function in the left kidney and normal right kidney, when compared to the previous DR scan. No scarring was mentioned in the report.

Due to ongoing concerns regarding reflux post-surgery, the DR with furosemide and voiding study was repeated after an interval of 1 year. The voiding study was repeated

at delayed intervals every hour for four hours, in an attempt to clear the kidneys and ureters of residual activity which rendered the last voiding study non-diagnostic. Unfortunately, despite this, results regarding reflux remained inconclusive. Figure 6 shows the interval perfusion and clearance curves. Figure 7 shows the new pre-post and delayed post-void static images for comparison.

	Left	Right
Relative Uptake Post (*)	38.3 %	61.7 %
Relative Uptake Ant (*)	N/A	N/A
Geometric Mean (*)	N/A	N/A
Area	48.4 %	51.6 %
Mean Uptake Quotient	N/A	N/A
*Background Corrected		

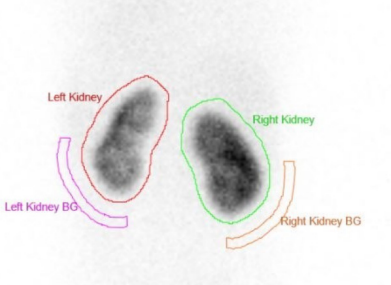


Figure 5. Image showing Static Renal Scintigraphy image, with the left (red) and right (green) renal split function. The featured images are reproduced courtesy of Oxford University Hospitals (OUH).

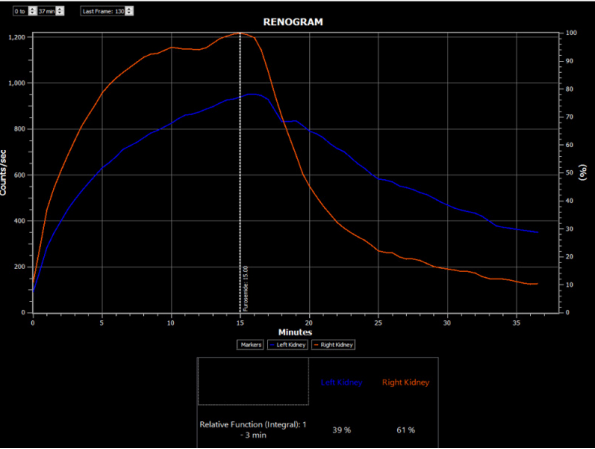


Figure 6. Image showing perfusion/clearance on the repeated study, one year later. The relative function of each kidney remains the same, although the right and left kidney curves appear slightly changed. The featured images are reproduced courtesy of Oxford University Hospitals (OUH).

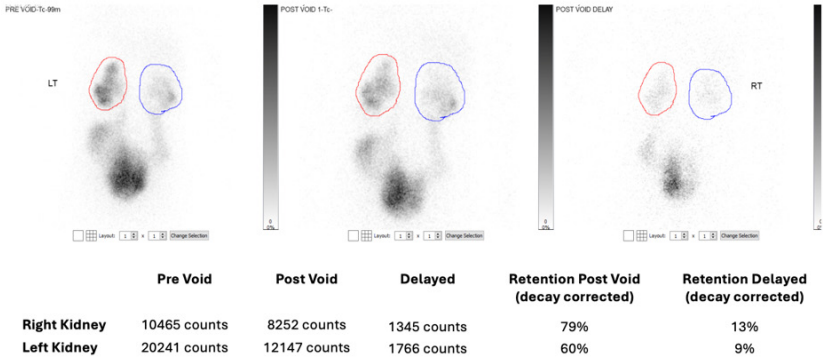


Figure 7. Static images showing pre-voiding study, post-voiding study and 1 hour delayed imaging. Percentage of retention in both the left (red) and right (blue) kidney is lower than the previous study, showing an improvement in the drainage. The featured images are reproduced courtesy of Oxford University Hospitals (OUH).

CONCLUSION

Providing diagnostic imaging in nuclear medicine for paediatric populations is a rewarding specialty, where the successful completion of complex exams offers technologists a great sense of achievement. However, it is recognised that paediatric studies are demanding and require a high level of staff skill to complete effectively. Protocols cannot be exactly replicated across children of all ages, which can make staff training and patient scheduling complex.

Technologists are encouraged not to be disheartened by this, but to see each study as an individual challenge to make the experience of the patient and the caregivers a positive one whilst obtaining high-quality diagnostic images.

Departments are advised to ensure adequate training and support is available for new staff when undertaking these studies in paediatric patients. Booking schedules should factor in the experience

of both patients and staff. Increased waiting times for patients can lead to anxiety and a risk of non-compliance, whereas intensive booking schedules can be mentally and logistically challenging for staff.

The author strongly believes that a cohesive multidisciplinary team and good communication between staff and caregivers are the key to success in these examinations. Teams should be encouraged to gather as much experience as possible in imaging of paediatric patients to build their confidence and proficiency in performing this type of scan.

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Direct and Indirect Radionuclide Cystography

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EXECUTIVE SUMMARY

Radionuclide cystography is a well-established nuclear medicine technique for the functional evaluation of the lower urinary tract in paediatric patients and plays a central role in the diagnosis and follow-up of vesicoureteral reflux (VUR). Introduced in 1959 as a functional alternative to conventional voiding cystourethrography, it allows continuous dynamic assessment of the bladder, ureters, and renal collecting systems, with a significantly lower gonadal radiation exposure.

Two approaches are used: direct radionuclide cystography (DRC), involving retrograde instillation of the radiopharmaceutical into the bladder via catheterisation, and indirect radionuclide cystography (IRC), performed after intravenous tracer administration during a renal dynamic study. The most used radiopharmaceuticals include ^{99m}Tc -DTPA and ^{99m}Tc -MAG3, both widely employed in nuclear medicine renal imaging. DRC provides higher sensitivity, particularly for low-grade or intermittent reflux, and enables quantitative evaluation of bladder capacity, post-void residual volume, and reflux timing, making it the preferred technique in infants, non-toilet-trained children, and high-risk clinical settings. IRC represents a non-invasive alternative suitable for older, cooperative children and allows simultaneous assessment of renal function.

This chapter reviews the clinical indications, patient preparation, radiopharmaceuticals, imaging protocols, image processing, and interpretation principles for both approaches, with emphasis on paediatric-specific technical aspects and the role of cine review and quantitative analysis. Clinical case examples

illustrate the integration of radionuclide cystography into the paediatric diagnostic and follow-up pathway.

Radionuclide cystography remains a safe, reproducible, and functionally informative imaging modality in paediatric urological imaging. The choice between direct and indirect techniques should be individualised according to patient age, cooperation, clinical context, and diagnostic goals.

Keywords: Radionuclide cystography; Vesicoureteral reflux (VUR); Paediatric nuclear medicine; Direct radionuclide cystography; Indirect radionuclide cystography; Low radiation exposure

INTRODUCTION

Radionuclide cystography (RNC), introduced in 1959, is a functional imaging technique for evaluating the lower urinary tract in paediatric patients, particularly in the diagnosis of vesicoureteral reflux (VUR) [1]. At that time, voiding cystourethrography (VCUG) was the standard method; however, although it demonstrates reflux, the latter provides limited information on bladder physiology and does not allow quantification of bladder capacity or reflux parameters [2]. The introduction of radionuclide imaging enabled continuous, real-time assessment of the bladder and upper urinary tract using a gamma camera, improving sensitivity for intermittent or low-grade reflux while significantly reducing gonadal radiation exposure compared with VCUG [2].

Two main approaches are used. Indirect radionuclide cystography (IRC), developed in the early 1960s, involves intravenous administration of a radiopharmaceutical that reaches the bladder through renal excretion; although minimally invasive, it depends on renal function and may miss low-volume

reflux [1]. Direct radionuclide cystography (DRC), using intravesical instillation via catheterisation, allows evaluation of the complete voiding cycle and quantitative assessment of bladder parameters with higher sensitivity, making it the preferred technique in many clinical scenarios [1, 2].

Radionuclide techniques have become central to paediatric nephro-urological imaging, particularly given the high prevalence of urinary tract infections, VUR, and congenital anomalies, and can be performed with standard gamma camera equipment in most centres [3].

CLINICAL INDICATIONS AND LIMITATIONS

1. Direct Radionuclide Cystography (DRC)

Clinical Indications [4]:

- » Detection of vesicoureteral reflux (VUR)
- » Follow-up of previously diagnosed VUR (assessment of progression or spontaneous resolution)
- » Screening for familial VUR (siblings/relatives of children with VUR)
- » Evaluation of bladder dysfunction (including measurement of post-void residual urine)

Limitations:

- » Not suitable when detailed anatomical evaluation of the urethra or bladder is required
- » Inadequate sphincter control may prevent proper assessment of the voiding phase

2. Indirect Radionuclide Cystography (IRC)

Clinical Indications [4]:

- » Alternative when catheterisation should be avoided, in cooperative children
- » Detection of VUR during a renal dynamic study already being performed
- » Evaluation of urinary drainage in cases of hydronephrosis or suspected obstruction

Limitations:

- » Lower sensitivity for detecting VUR compared with the direct method, especially in cases of suspected low-grade/intermittent reflux
- » Requires patient cooperation to hold urine and void on command, limiting use in young infants
- » Does not provide anatomical detail of bladder or urethra and does not allow reflux grading

Patient Preparation and Aftercare

Preparation begins before the examination day.

During the clinic consultation, the purpose of the study and the steps of the procedure are explained to both parents and child. Once the referral is made, the nuclear medicine technologist reviews the clinical information to ensure that the radiation exposure is justified. This includes checking the medical history, ultrasound results and previous imaging. Because children are more sensitive to ionising radiation than adults, justification is essential, and alternative diagnostic methods with lower

radiation must be considered in advance [3].

Parents receive written information ahead of the scheduled examination. The instructions clarify that fasting is not required for the procedure and outline what to expect on the day of the study. They include practical details such as the anticipated waiting period between the radiotracer administration and image acquisition, the approximate duration of the examination, and the need to ensure that the child arrives well hydrated, as this facilitates bladder filling and improves the quality of the study [5].

On the day of the examination, the environment should minimise anxiety. Nuclear medicine technologists are responsible for creating a calm and child-friendly setting, for example, by using decorations, toys, videos, music, and warm lighting. Technologists should actively involve the parents, as their presence offers reassurance and helps maintain cooperation throughout the procedure [3].

Good preparation, pain control, distraction techniques and gentle immobilisation (e.g. using vacuum cushions, sandbags, or Velcro straps) usually allow children to remain still during image acquisition. Effective patient preparation combined with parental involvement and appropriate technical set-up improves image quality and reduces artefacts [2,3]. DRC involves urethral catheterisation for retrograde instillation of the radiopharmaceutical, as detailed in the DRC section below [3].

Radiopharmaceutical and Activity

1. Direct Radionuclide Cystography

In the direct technique, the radiopharmaceuticals commonly used include ^{99m}Tc -stannous diethylenetriamine penta-acetic acid (DTPA), ^{99m}Tc -sulphur colloid, or technetium-99m (^{99m}Tc) in the form of sodium pertechnetate [4].

Typically, an administered activity of 18.5 to 37 MBq (0.5 to 1.0 mCi) is introduced aseptically into the bladder via a urethral catheter. For infants and toddlers, a lower activity of 9 MBq to 18.5 MBq (0.25 to 0.5 mCi) may be used [4].

2. Indirect Radionuclide Cystography

For the IRC, ^{99m}Tc -MAG3 is generally preferred due to its higher extraction efficiency and superior target-to-background ratio. IRC is performed following intravenous tracer administration during a standard renal dynamic scintigraphy, with cystographic images acquired once sufficient activity has accumulated in the bladder as a result of renal excretion. The activity administered for the renal scintigraphy should be adjusted to the child's body weight and kept as low as reasonably possible to ensure diagnostic image quality. The administered activity must be calculated according to the most recent version of the EANM dose card [2].

^{99m}Tc -MAG3 is mainly eliminated through tubular secretion and is cleared rapidly from the body. This fast clearance results in lower background activity and reduced tracer retention in the kidneys, thereby improving image quality. MAG3 is the preferred tracer for indirect radionuclide cystography in children due

to its higher protein binding and superior extraction fraction compared to ^{99m}Tc -DTPA (approximately 40% versus 20%), which allows better visualisation of urinary drainage and reflux. The minimum administered activity is approximately 20 MBq (0.5 mCi), with higher activities adjusted according to body weight following EANM recommendations [6].

INJECTION TECHNIQUE

1. Direct Radionuclide Cystography

The DRC technique involves retrograde instillation of a diluted radiotracer solution into the bladder through aseptic catheterization. According to the European Association of Nuclear Medicine (EANM) Guidelines for Direct Radionuclide Cystography in Children [3], the full radiotracer dose is first diluted in 10 mL of normal saline (NaCl) and instilled into the bladder, followed by gradual filling with saline up to the estimated bladder capacity. The filling is performed by gravity to avoid overpressure and vesicoureteral reflux artefacts.

Mandell et al. [1] detailed the procedural steps: after appropriate explanation to the child and family members, the patient voids, and the bladder is catheterised under sterile conditions. The radionuclide is then instilled, using warmed saline to reduce bladder spasm. The bladder capacity can be estimated using the formula: $(\text{age} + 2) \times 30$ millilitres.

Key technical considerations include aseptic technique, use of warmed saline, and maintaining a calm environment to minimise distress to the patient [1, 3]. The catheter should be flushed with 10–20 mL of normal saline before and after tracer

instillation to prevent mucosal irritation and reduce contamination [4]. The radiotracer is mixed in saline (approximately 250–500 mL) and instilled by gravity until the calculated bladder capacity or the child's urge to void is reached [3, 4]. Sequential dynamic images are obtained during filling, voiding, and post-void phases to evaluate reflux severity and timing [3].

Catheterisation procedures are usually performed by a paediatric team, requiring effective coordination with the nuclear medicine technologists, as well as with the child and their parents or caregivers. It is advisable to allow a longer time slot for these patients, in case they require additional time, patience or reassurance.

2. Indirect Radionuclide Cystography

In the indirect technique, the radionuclide is administered intravenously, and reflux is assessed during the renal dynamic scintigraphy. The EANM Guidelines for Indirect Radionuclide Cystography [2] state that no catheterisation is required, but that correct intravenous injection, hydration, and bladder management are essential for diagnostic accuracy. Given that most hospital cannulation procedures take place in the paediatric ward, close coordination with the paediatric team is mandatory.

A reliable peripheral intravenous access should be secured for a compact bolus injection of ^{99m}Tc -MAG3 or ^{99m}Tc -DTPA [2, 6]. A cannula is normally preferred rather than a butterfly, since it is more stable, leading to a higher chance of successful administration.

Adequate hydration, oral or intravenous depending on the patient's age, and bladder emptying before radiotracer injection are

mandatory. Dynamic renal images are acquired during the uptake and drainage phases, followed by observation of bladder filling and the voiding phase to identify possible vesicoureteral reflux [2]. Extravasation at the injection site must be avoided as it can distort time–activity curves and delay bladder visualisation [4]. While IRC is less sensitive for low-grade reflux than DRC, it offers the advantage of

being non-invasive and allows assessment of renal function in the same session [2].

IMAGING PROTOCOL AND IMAGE PROCESSING

1. Direct Radionuclide Cystography

Imaging Protocol	
Imaging Equipment	Gamma camera with a low-energy, high-sensitivity collimator
Imaging Phases	Dynamic imaging during filling, voiding, and post-void phases
Patient Positioning	Supine position with posterior camera centred over bladder and kidneys to include both ureters; cooperative children may void seated or standing with anterior or posterior views [1, 3]
Acquisition Parameters	2–4 s per frame during filling; 1 s per frame during voiding
Matrix Size	64×64 or 128×128, depending on patient size and system sensitivity [3, 5]
Imaging Approach	Continuous dynamic acquisition to detect transient reflux episodes not visible on static images [6]
Comfort Measures	Calm environment, blankets, room temperature adjustment, and distractions (videos, music, toys) to improve comfort and cooperation
Privacy and Sensitivity	Attention to comfort and privacy is essential, as anxiety, shyness, or embarrassment may impair voiding and compromise exam completion

Processing	
Image Review	Image sequences are reviewed in cine mode to identify the onset, timing, and severity of reflux
Regions of Interest (ROIs)	ROIs are drawn over the kidneys, ureters, and bladder, and appropriate background regions for background correction
Time–Activity Curves	Generated from ROIs to determine whether reflux occurs during filling or voiding phases [3, 6]
Post-Processing Steps	Background subtraction, temporal smoothing, and normalisation of counts to acquisition duration
Reflux Grading Method	Semi-quantitative grading based on tracer distribution: Grade I: Activity confined to the renal pelvis only [1, 3] Grade II: Activity extending into the pelvicalyceal system [1, 3] Grade III: Persistent cortical activity indicating higher-grade reflux [1, 3]

2. Indirect Radionuclide Cystography

Imaging Protocol	
Initial Imaging Phase	Dynamic renal imaging starts immediately after injection, including both kidneys and bladder in the posterior view
Renogram Acquisition Parameters	1–2 s per frame for the first 60 s, followed by 10–15 s per frame for 20–30 min, using a standard renogram protocol [2, 6].
Bladder Preparation	Bladder emptying prior to tracer injection is recommended to standardise bladder dynamics and optimise evaluation of reflux during voiding [4]
Transition to Voiding Phase	Upon completion of the renogram and once the bladder is adequately filled, the child is repositioned
Patient Positioning During Voiding	The child is positioned sitting or standing with their back against the gamma camera head to include kidneys, ureters, and bladder within the field of view (posterior projection). Image acquisition should be initiated before instructing the patient to void to avoid missing the onset of micturition, particularly in boys with a full bladder
Voiding Phase Acquisition	Dynamic imaging continues during voiding at 1 s per frame
Strategies to Encourage Voiding	Techniques such as reassurance, privacy, running water sounds, or placing the feet in cold water may be used to facilitate voiding
Contamination Risk and Management	Due to patient positioning and the nature of voiding imaging, there is a potential risk of radioactive contamination; appropriate protective measures should be in place, and contingency actions (e.g. prompt cleaning and repeat acquisition if necessary) should be planned



Figure 1. Representation of the gamma camera prepared for a paediatric patient (adapted from the Nuclear Medicine Service, Fribourg Cantonal Hospital, in Switzerland)

Processing	
Regions of Interest (ROIs)	ROIs are drawn over the kidneys, ureters, bladder, and background
Time–Activity Curves	Used to assess renal drainage patterns and identify reflux events
Cine Review	Cine display is essential to detect brief or low-volume reflux episodes that may be missed on static images [2]
Motion Correction	Motion correction techniques may be applied in restless children to reduce motion artefacts
Diagnostic Advantage of IRC	IRC provides combined functional and morphological assessment of renal drainage and vesicoureteral reflux in a single low-dose study [2, 4]
Paediatric Imaging Challenges	Small organ size and variable patient cooperation require careful optimisation of imaging parameters [1, 2, 3, 4, 5]
Acquisition Optimisation	Short frame times and fully dynamic acquisition are recommended to minimise motion-related artefacts [1, 5]
Image Processing Techniques	Iterative filtering and background subtraction enhance image contrast in low-count paediatric studies
Mandatory Cine Display	Required due to the intermittent and often low-grade nature of reflux
Quantitative Assessment	Quantification of reflux volume, bladder capacity, and post-void residual is recommended, particularly for follow-up after surgical correction of reflux [2, 3]

IMAGE INTERPRETATION
General Principles

The interpretation of radionuclide cystography relies on identifying VUR events and grading their timing, extent, and persistence during the study. Both direct and indirect techniques allow dynamic assessment of urinary flow from bladder to ureters and kidneys, providing functional information beyond morphological detail.

Image sequences must be reviewed in cine mode to capture transient reflux events that could be missed on static frames. The reader should evaluate the filling phase, voiding phase, and post-void residual activity separately [1, 2].

A positive study is defined by the appearance of radioactivity in the ureters or renal pelvis outside of the expected sequence of filling. The grade of reflux is

based on the extent of radiotracer migration and its persistence after voiding [1, 3, 6].

1. Direct Radionuclide Cystography

In direct studies, reflux can occur either during bladder filling or voiding. Physiological low-grade reflux limited to the distal ureter may occasionally occur in infants and should not be misinterpreted [1]. According to the EANM Guidelines for DRC in Children [1], the following semi-quantitative grading is recommended:

- » **Grade I** – Activity limited to the ureter
- » **Grade II** – Activity extending into the renal pelvis without calyceal visualisation
- » **Grade III** – Activity reaching the calyces or parenchyma, persistent after voiding

The timing of reflux (filling vs. voiding phase) should be recorded, as voiding-phase reflux often correlates with higher clinical significance [1, 3]. Careful differentiation between true reflux and artefacts such as extravascular contamination, catheter leakage, or bowel activity is essential [2, 5].

2. Indirect Radionuclide Cystography

In the indirect technique, reflux is detected after intravenous injection of [^{99m}Tc]Tc-MAG following a renal dynamic scintigraphy. Activity ascending from the bladder into one or both ureters indicates reflux [5].

The EANM Guidelines for IRC [2] highlight that renogram time-activity curves are key to confirming reflux events. A reflux episode appears as a sudden rise in the upper-tract curve concurrent with increased bladder counts. The magnitude and duration of this rise reflect reflux severity [2]. A normal study shows continuous wash-out from kidneys to bladder without reverse flow. Persistent renal activity after voiding suggests either high-grade reflux or impaired drainage [4, 2]. Common pitfalls include extravasation at the injection site, patient movement, and superimposed bowel activity that can simulate ureteral activity. Cross-referencing of dynamic cine with quantitative curves is essential for confirmation [2, 5].

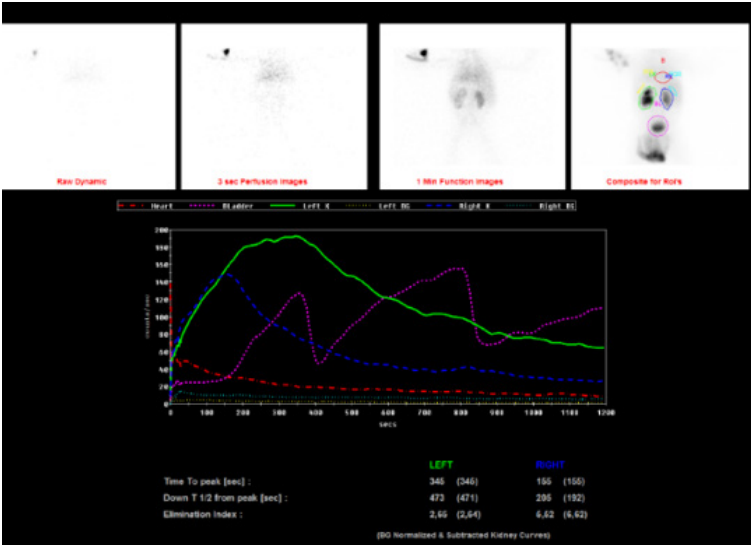


Figure 2. IRC in a 15-month-old girl. Both kidneys show normal function. The left kidney demonstrates mild pelvicalyceal dilation with good drainage, while the right kidney drains normally. Image courtesy of the Nuclear Medicine Department, Cantonal Hospital of Fribourg.

Clinical Correlation and Reporting

Reports should specify reflux occurrence (positive/negative), timing (filling, voiding, or both), laterality, and residual post-void activity. Grading of reflux with IRC is limited and not reliably performed; however, reflux reaching the renal collecting system is generally considered clinically significant. For follow-up, comparison of reflux presence and timing is crucial [3, 5]. The low radiation exposure and functional assessment make radionuclide cystography ideal for serial evaluation of paediatric VUR [1, 5, 6].

Patient Pathway (Examples of Clinical Cases)

Introduction

The patient pathway in paediatric radionuclide cystography typically begins with a urinary tract infection or hydronephrosis detected on ultrasound, leading to suspicion of VUR.

The choice between direct and indirect radionuclide cystography depends on the patient's age, continence, and clinical presentation [1, 2].

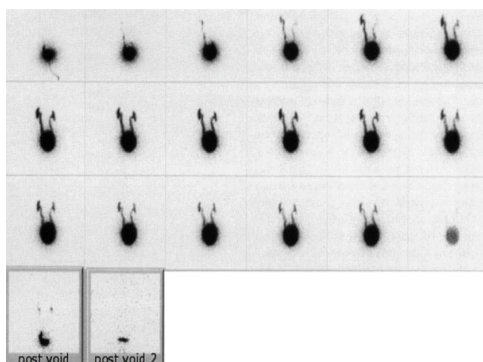


Figure 3. Dynamic posterior representative images show radiotracer reflux from the bladder into the left ureter and renal pelvis during voiding, consistent with Grade III vesicoureteral reflux [7].

In general, infants and non-toilet-trained children undergo DRC due to the need for catheterisation, while older, toilet-trained children may undergo IRC following a renal dynamic scintigraphy [1, 3].

The following clinical examples illustrate the practical application of both approaches and the interpretation of results.

Clinical Case 1 – Infant with recurrent febrile urinary tract infection

A 9-month-old girl with recurrent febrile UTI underwent ultrasound, revealing mild left renal pelvic dilatation. DRC was selected due to her age and clinical history [2].

Procedure: The bladder was catheterised, and [^{99m}Tc]Tc-pertechnetate diluted in saline was instilled by gravity. Dynamic posterior images were obtained during filling and voiding [1, 3].

Findings: Cine review showed reflux of tracer into the left ureter and renal pelvis during the voiding phase, persisting after bladder emptying — consistent with Grade III VUR [1].

Outcome: Antibiotic prophylaxis was continued, and follow-up DRC at 12 months showed resolution of reflux [3].

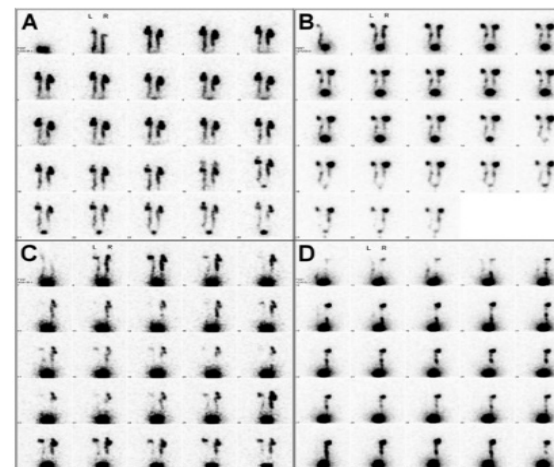


Figure 4. Posterior radionuclide cystography representative image demonstrating retrograde tracer flow into the ureter and renal pelvis during voiding, compatible with Grade III vesicoureteral reflux [8].

Clinical Case 2 – Catheter malposition during DRC

A 15-year-old girl was referred for DRC after a history of urinary incontinence post-surgery. During the examination, unusual bladder filling dynamics were noted, and the distribution of activity suggested catheter malposition [6].

Findings: Dynamic frames demonstrated extravascular tracer accumulation anterior to

the bladder outline, without normal bladder filling. The study was immediately stopped. A fluoroscopic check confirmed that the catheter balloon was inflated within the urethra, not the bladder [6].

Outcome: The catheter was repositioned, and a repeat DRC the next day showed normal bladder filling with no reflux. The patient recovered without complications.

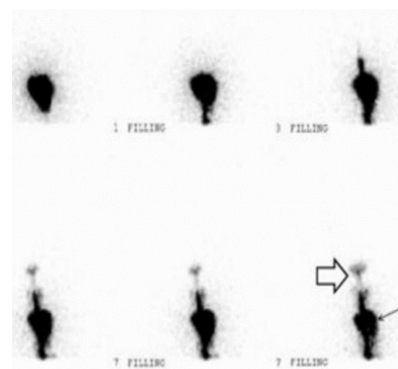


Figure 5. Illustrative example of catheter malposition during direct radionuclide cystography. The radiotracer accumulates outside the expected bladder outline, indicating incorrect placement of the catheter balloon. This example is not from the original patient [6].

DISCUSSION AND CLINICAL INTEGRATION

These cases demonstrate the flexibility of radionuclide cystography in the paediatric diagnostic pathway:

» Case 1 illustrates the value of DRC in high-risk infants with febrile UTI, providing sensitive detection of high-grade reflux with minimal radiation exposure [1–3].

» Case 2 underlines the importance of technical vigilance, as incorrect catheter placement can mimic reflux or cause false-negative results [4].

Overall, radionuclide cystography offers a safe, repeatable, and functionally informative assessment of the urinary tract, forming an essential part of the paediatric patient pathway from diagnosis through to follow-up.

CONCLUSION

Radionuclide cystography, in both direct and indirect forms, plays an important role in the evaluation of the paediatric lower urinary tract, particularly for the diagnosis and follow-up of vesicoureteral reflux and recurrent urinary tract infections. Compared with conventional voiding cystourethrography, it provides continuous functional assessment with lower radiation exposure and greater sensitivity for intermittent or low-grade reflux.

Although indirect radionuclide cystography is less invasive, the lower sensitivity may restrict its usage in certain clinical contexts. Direct radionuclide cystography enables comprehensive assessment of the voiding cycle and remains the preferred technique in younger children and when precise reflux characterisation is required. Overall, radionuclide cystography is a safe and reproducible functional imaging modality, and technique selection should be individualised according to patient age, cooperation, clinical indication, and diagnostic objectives, with appropriate preparation and technical optimisation essential for accurate interpretation.

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3.2

PET/CT in Paediatrics

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EXECUTIVE SUMMARY

This chapter outlines best-practice principles for delivering safe, patient-centred paediatric nuclear medicine positron emission tomography / computed tomography (PET/CT) services. The focus is on minimising sedation, optimising diagnostic quality, and ensuring a supportive environment for children and families.

» Paediatric-Centred Planning

Care is individualised through age-appropriate communication, active parent involvement, and preparation techniques that minimise anxiety and encourage cooperation. Where required, sedation or general anaesthesia (GA) is to be coordinated with relevant multi-disciplinary teams to ensure appropriate fasting while maintaining scan quality and clinical relevance.

» Supportive Environment

A calm, low-stimulus clinical environment is prioritised to reduce stress and behavioural escalation. Simple rehearsal and play-based strategies enhance cooperation and decrease sedation reliance.

» Safety and Metabolic Management

For [¹⁸F]FDG PET, blood glucose levels are checked prior to radiopharmaceutical administration. Fasting schedules are synchronised with sedation timing, and local paediatric diabetes guidance is applied when relevant.

» Optimised Dosing and Imaging Harmonisation

Administered activity aligns with established paediatric dosing standards. Residual activity is quantified and

subtracted to calculate net delivery, and CT parameters are optimised for patient size. All settings are documented to ensure transparent, harmonised and high-quality imaging.

» Immobilisation, Comfort, and Artefact Reduction

Non-distressing immobilisation techniques, bladder voiding, warmth, and distraction strategies are applied to reduce motion artefact, enhance comfort, and minimise the requirement for unnecessary sedation.

Keywords: paediatric-centred care; family; preparation; glucose; immobilisation; flexible

INTRODUCTION

Positron emission tomography/computed tomography (PET/CT) has rapidly evolved into a vital paediatric imaging tool, progressing from a niche technique to a cornerstone modality that delivers precise, low-dose, clinically meaningful insights into childhood disease.

Paediatric PET/CT differs significantly from adult imaging due to the unique physiological, developmental, and psychosocial needs of children. Younger patients have higher metabolic rates and smaller body sizes, requiring age- and weight-adjusted radiopharmaceutical dosing as well as tailored low-dose CT protocols. Motion management is a greater challenge in paediatrics, necessitating child-friendly preparation strategies, distraction techniques, or the use of anaesthesia in selected cases. The presence of parents or carers during scan preparation and the radiotracer uptake period is also integral to ensuring patient cooperation and emotional comfort. Additionally, normal patterns of

tracer distribution vary with growth and development, demanding specialised paediatric expertise for accurate image interpretation. These differences make paediatric PET/CT a distinctly specialised practice that relies on technologists skilled in both technical optimisation and compassionate, family-centred care.

PET/CT has become vital in aiding the diagnosis, treatment monitoring, and detection of disease recurrence for many paediatric pathologies and disease processes. This chapter focuses predominantly on [¹⁸F]FDG, the most widely utilised radiotracer in PET imaging, with other radiotracers briefly discussed in the concluding section.

Below are some of the most common indications for PET/CT in children [1].

Oncology

PET/CT is widely used across paediatric oncology to assess disease extent, treatment response, and surveillance. Common indications include:

- » Hodgkin and non-Hodgkin lymphoma
- » Sarcomas
- » Neuroblastoma and other neuroendocrine tumours (NETs)
- » Central nervous system (CNS) tumours, including high-grade gliomas
- » Other solid tumours, such as germ cell tumours and Langerhans cell histiocytosis (LCH)

Neurology

[¹⁸F]FDG PET/CT is frequently used in the evaluation of epilepsy, particularly for identifying hypometabolic regions that correspond to potential epileptogenic zones. Interictal PET scans typically demonstrate reduced glucose metabolism in epileptic foci relative to surrounding brain tissue. When co-registered with current MRI and/or ictal cerebral perfusion single-photon imaging, PET/CT can support localisation of seizure onset zones and assist in guiding surgical planning.

Infection / Inflammation

PET/CT plays a key role in detecting and characterising infectious and inflammatory conditions. Common indications include:

- » Fever of unknown origin (FUO)
- » Occult infections, such as endocarditis
- » Autoimmune or inflammatory diseases, including vasculitis, sarcoidosis, and chronic granulomatous disease (CGD)

It is also valuable for assessing infection associated with implanted devices, monitoring treatment response, and in guiding biopsy by distinguishing active inflammatory sites from inactive or resolved disease.

Other Indications

Additional specialised paediatric uses include:

- » [¹⁸F]FDOPA PET/CT or alternatively [⁶⁸Ga] Ga-DOTA-TATE PET/CT may be used in congenital hyperinsulinism – differentiating focal from diffuse disease and informing surgical decision-making;

» ^[18F]FDG PET/CT may be used in post-transplant lymphoproliferative disease (PTLD) or bowel graft-versus-host disease (GVHD)

IMPORTANCE OF A CHILD-CENTRED APPROACH

Children are not small adults; effective paediatric PET/CT requires care adapted to the developmental stage and emotional needs of that individual child. A child-centred approach improves cooperation, reduces anxiety-related motion artefact, and may avoid sedation. Techniques include age-appropriate explanations, parental involvement, play therapy, structured distraction, and child life specialist support. These measures are strongly advocated in the European Association Nuclear Medicine (EANM) paediatric procedural recommendations and paediatric imaging literature [2].

The **'ONE VOICE'** approach can be applied by all staff during the procedure:

- » **One voice** at a time during the procedure
- » **Need** to offer a role to the parent – encourage involvement and acknowledge their capacity to assist the child in feeling calm and reassured.
- » **Educate** the child and family before the procedure about what to expect.
- » **Validate** the child with words and gestures. Encourage them and acknowledge behaviours that are helpful to complete the procedure. Otherwise acknowledge what was difficult for them.

» **Offer** the most comfortable non-threatening position. Children often feel more in control and less anxious when they are sitting up.

» **Individualise** your game plan. Find out what has worked well before and what has not, especially for special needs children.

» **Choose** appropriate distraction techniques to be used.

» **Eliminate** unnecessary people not actively involved in the procedure. Fewer people and less noise mean that the procedure / process is less intimidating.

Family-centred care improves cooperation and reduces the need for sedation. Invite a calm and pre-coached caregiver into the preparation area or uptake areas. Set clear expectations using age-appropriate and developmentally appropriate language (e.g. "camera pictures" or "special sugar") and allocate roles for caregivers (e.g. "can you hold the tablet and read the story"). Employ developmentally appropriate distraction techniques (e.g. bubbles for toddlers; videos for school-age children; choice and privacy for adolescents). Involve child play therapists, if available, or use play time in the department to increase the proportion of successful non-sedated scans while improving patient experiences [3–5].

Practical tip: Ensure the family are aware of the one-voice technique, avoid negatives (such as "don't move") in favour of positive instructions (e.g. "keep your tummy still like a statue") and rehearse stillness for a timed 60–90 seconds to promote successful imaging prior to radiotracer injection and uptake.

From a safety perspective, strict adherence to As Low As Reasonably Achievable (ALARA) principles is essential, particularly for the CT component. Low-dose CT protocols should be used for attenuation correction (AC) or localisation unless diagnostic CT is clinically indicated. Because parents and carers frequently remain with the child during preparation and may be present in the uptake room or scanner area, depending on local policy, clear guidance must also be provided to them to ensure that their radiation exposure is minimised. This includes reinforcing distance, shielding, and time-based strategies, along with clear instructions about when they may assist and when they must step away. In addition, comprehensive post-procedure radiation safety information must be provided to families to support safe interactions with the patient when at home, especially with siblings, pregnant individuals, and other vulnerable contacts.

Practical tip: Clearly communicate radiation safety principles to the parent or carer and provide any post-procedure instructions. Confirm the pregnancy status of any parents or carers supporting the patient before the procedure. Limit the number of additional people present during the procedure, including siblings.

PATIENT PREPARATION

Patient preparation is one of the most important determinants of scan quality and ultimately sets the study up for success or failure. Preparation begins even prior to booking, as choosing a sedation or non-sedation pathway requires early discussion with the family and clinical team to confirm suitability and planning. For ^[18F]

FDG PET, anticipate brown fat activation and skeletal muscle uptake, especially in cold climates or air-conditioned hospitals, and advise families during booking or confirmation calls to dress the child warmly, allow extra time for a calm arrival, follow an age-appropriate fasting plan, and, if possible, maintain hydration with plain water. Begin warming the room before injection and maintain a warm, low-stimulus environment throughout uptake using practical measures such as forced-air warmers, beanies, socks, and metal-free layered clothing, allowing items to remain on during the scan without creating artefacts.

Practical tip: Keep uptake conditions calm and the environment warm. Avoid talking, chewing, crying, or unnecessary movement during the uptake phase to minimise unwanted muscle and brown fat uptake.

GENERAL FASTING CONSIDERATIONS

Preparation aims to ensure optimal tracer biodistribution and reproducibility. For ^[18F]FDG PET, fasting for 4–6 hours (age-appropriate) with the intake of water being permitted is the standard practice and reduces insulin-mediated muscular uptake. Blood glucose should ideally be ≤10 mmol/L (≤180 mg/dL) at injection, with specific planning required for children having diabetes, as described in the Australian and New Zealand Society of Nuclear Medicine / Australian Diabetes Society (ANZSNM / ADS) 2024 joint guideline [6]. Strenuous exercise should be avoided for at least 24 hours before the examination, and children should remain warm and rest quietly during the uptake phase to minimise brown fat and muscular uptake. For ^[18F]F-DOPA, ^[18F]FET

and [¹¹C]-methionine, four-hour fasting instructions may be considered to maintain consistent preparation instructions across multiple PET tracers.

Fasting considerations for younger patients – sedation and/or general anaesthesia

In younger children and infants, fasting must balance the patient’s metabolic requirements with anaesthetic safety. If sedation or general anaesthesia is required, standard anaesthetic fasting rules should be followed: 2 hours for patients on clear fluids and 4 hours for patients taking breast milk, but always refer to local policies in any case.

If sedation or general anaesthesia is required, coordinate early with the anaesthetic team and confirm whether support is needed for uptake phase, imaging, or both. Ensure clear communication with the referring team, ward, and anaesthetics regarding the need to avoid dextrose-containing fluids during fasting and uptake.

Under general anaesthesia, thermoregulation is impaired and metabolic heat production falls while body temperature redistribution increases heat loss, so proactive warming is essential (in paediatrics, core temperature typically drops 1–1.5 C in the first hour without active warming) [7]. Where appropriate, supplement environmental warming with local-policy pharmacological strategies for brown fat uptake suppression (e.g. using low-dose beta-blockers or benzodiazepines) and document timing relative to injection for interpretation; note that practices vary internationally,

and environmental warming remains the first-line method of choice.

Sedation planning should occur at the time of booking, with a preference for non-pharmacological strategies wherever appropriate. A contingency motion-tolerant protocol (e.g. reduced time per bed position or targeted bed acquisitions) should be prepared in advance. Where feasible, be prepared to prioritise non-pharmacological approaches supported by shorter acquisitions and emerging motion correction techniques, which may reduce the need for sedation in selected patients.

Practical tip: Consider having a “Plan B” motion-tolerant protocol before opting to use sedation. This may include a higher bed speed, shorter list-mode acquisition, and/or repeat targeted bed positions if needed. Avoid dextrose-containing fluids during uptake.

SPECIFIC PATIENT PREPARATION CONSIDERATIONS

When [¹⁸F]FDG is used to investigate inflammatory or infiltrative cardiac disease in children, the goal is to suppress normal myocardial [¹⁸F]FDG uptake so that abnormal uptake is clearly visible. Preparation must be safe, developmentally appropriate, and guided by validated paediatric PET principles.

Considerations should include: [8–10]

RADIOPHARMACEUTICAL CONSIDERATIONS

As [¹⁸F]FDG is the most common radiopharmaceutical for paediatric PET, an understanding is required of how FDG

Preparation	Rationale
High-fat, low-carbohydrate dietary preparation 48 hours prior	Reduces circulating insulin and shifts metabolism toward free fatty acid use, decreasing myocardial glucose uptake
Avoid vigorous activity and exercise 24 hours prior	Physical activity increases glucose utilisation in myocardium and skeletal muscle, reducing suppression of physiological carbohydrate metabolism
Extended fast (overnight) with intake of water only	Fasting lowers circulating insulin, helping shift the myocardium to free fatty acid metabolism
Heparin prior to [¹⁸ F]FDG injection (selected cases only)	Promotes free fatty acid release via lipoprotein lipase activation, enhancing myocardial suppression. Use must only be considered after careful risk assessment and adherence to local paediatric protocols.

behaves in growing children, and how metabolic rates and physiological uptake patterns differ from those in adults. [¹⁸F]FDG is a glucose analogue which is labelled with a positron-emitting isotope; it is transported into the cells by glucose transporters (GLUT) and trapped in the cells after phosphorylation, thereby reflecting glycolytic activity [1]. Children often have higher physiological uptake in brown fat, brain, and active lymphoid tissue due to faster metabolic turnover, which can influence lesion detectability and background contrast. Calm, warm uptake conditions can help minimise unwanted uptake in muscles and brown fat, reducing artefacts and optimising diagnostic accuracy [11].

Activity administered

Dose optimisation is essential in paediatric PET imaging to achieve diagnostic-quality imaging using the lowest reasonable amount of administered activity (ALARA principle). Modern PET cameras provide

increased sensitivity via improved detectors and advanced reconstruction algorithms. Injected activity should be weight-based and consistent with the EANM Paediatric Dosage Card or SNMMI consensus guidelines for paediatric administered radiopharmaceutical activities. Further dose reduction without compromising diagnostic quality can be achieved using modern digital or Extended Field of View (EFOV) PET systems [12–13].

These technological improvements also allow reduced acquisition times, which can improve patient compliance, minimise motion artefact, and enhance overall workflow. Regular protocol review and image quality audits are recommended to ensure ongoing optimisation of both dose and acquisition parameters. Technologist-led auditing plays a key role in refining practice and reducing unnecessary patient exposure.

Practical tip: Ensure consistent uptake time to help maintain reproducibility. When using newer PET systems (e.g. digital PET), consider incrementally lowering

administered activity or acquisition parameters as local experience grows, supported by technologist-led optimisation audits.

INJECTION TECHNIQUE

Reliable intravenous (IV) access is critical to avoid extravasation and altered radiotracer biodistribution. A peripheral IV cannula is preferred in most children, with careful site selection, patency confirmation, and secure fixation. When clinically feasible, IV access should be established contralateral to the area of clinical interest to minimise the risk of confounding focal uptake. If this is not achievable, meticulous flushing before and after administration is essential. Butterfly needles should generally be avoided due to the higher risk of dislodgement and extravasation.

Existing central venous access devices (CVADs) may be used when peripheral access is not suitable, provided patency is confirmed and institutional flushing protocols are followed. The possibility of focal uptake at the administration site — whether peripheral cannula or CVAD — should be considered both prior to radiopharmaceutical administration, particularly in relation to the anatomical area of interest, and during subsequent image interpretation.

THE IMAGING PROCEDURE

Paediatric imaging should be patient-centred, and planned around image quality, motion risk, dose optimisation, and child comfort. The aim is to obtain reproducible diagnostic images at the lowest reasonable radiation exposure. In practice, this means positioning the patient supine with the arms raised whenever this is tolerated and adopting smart immobilisation techniques

matched to patient age and tolerance (e.g. vacuum bags or swaddling for infants; soft straps and wedges for older children). Throughout the scan, balance comfort against motion-free imaging by coaching the child in simple, positive language while keeping the parent engaged and informed. If a parent remains in the room, provide radiation safety education (where to stand, when to step back) and assign a specific supportive role to reduce anxiety and movement. Where image quality is compromised in a single region, the focus should be on re-imaging that area (repeat targeted bed positions) rather than on repeating the entire scan, documenting any deviations (e.g. arm position, interruptions, re-imaging, or reconstruction changes) to preserve standardised uptake value (SUV) comparability and support high-quality reporting.

Ensure consistent departmental record-keeping including fasting status, blood glucose level, sedative administration and precise injection to scan timing to support consistent and reproducible image quality. Document recent treatments, such as chemotherapy, radiation therapy, or immunotherapy, as well as recent surgery or other invasive procedures and any relevant clinical symptoms or complaints (e.g. pain or trauma). In cases of suspected infection or inflammation, document recent febrile episodes, antibiotic use, and any procedures that may influence tracer biodistribution.

Practical tip: Encourage parents to be actively engaged. For example: “If you were reading that book in the uptake room, please keep reading it now while we start the pictures.” Give them specific roles (e.g. hold the book/tablet, use one hand to hold your child’s hands, and maintain one calm voice). Show them where to stand

safely and demonstrate how they can remain present during the scan, such as by holding their child’s hands. This consistently reduces patient anxiety and motion without increasing radiation dose.

NORMAL IMAGING VARIANTS / PITFALLS

In paediatric PET/CT, artefacts and pitfalls are common, so technologists and clinicians must recognise physiological and age-specific normal variants to avoid false positives and false negatives unique to children. Suboptimal acquisition or post-processing can adversely affect interpretation and may even lead to misdiagnosis; therefore, prioritise post-processing controls before interpretation. Limiting motion and minimising any misregistration is essential, as is reviewing the non-attenuation-corrected (NAC) data to confirm any attenuation or movement-related artefacts that can affect the AC data. Correlating with prior imaging and the

clinical context remains an important part of accurate interpretation.

Dose filtration (post-reconstruction smoothing/kernel choices to manage low-count noise) directly influences image appearance and SUVs. Heavier smoothing reduces noise but can blur small lesions, lower apparent uptake, and mask subtle physiological patterns (e.g. brown adipose tissue or bowel activity), whereas inappropriate filters may over-homogenise organ edges (e.g. adrenals, pancreas) and conceal normal heterogeneity. Always document any changes to standard imaging post-processing parameters to ensure SUVs remain comparable across visits and avoid attributing reduced lesion conspicuity to “dose” or “motion” when filter selection is the true cause. Because post-processing alterations can impact the results, technologists should understand the effects of such changes before making any modifications.

Aspect	Impact
Noise reduction	Heavy filtering can mask subtle physiological uptake , making normal variants (e.g. brown fat, bowel) harder to recognise.
Spatial resolution loss	Over-smoothing can blur small true lesions , mimicking normal background.
Apparent uptake reduction	Filtering can lower measured SUV, making pathological uptake look physiological .
Edge definition	Poor filtration selection may make organs (e.g. adrenal glands, pancreas) appear more homogeneous than they are, concealing normal heterogeneity .

Table 1. Common post-processing impacts that can affect imaging outcomes.



Figure 1: Maximum intensity projection images of FDG PET CT scans in a 12 year old male with osteosarcoma of the right distal femur. The staging study (a) before treatment shows the intensely FDG avid tumour in the right distal femur (open arrow). There are no other sites of disease but physiologic FDG activity is seen in a normal thymus appearing as diffuse triangular, sail-shaped FDG uptake in the mediastinum (closed arrow), physiologic intense activity of lymphoid tissue in the oro-pharynx (closed arrow head), linear uptake at sites of physiologic bone growth plates (open arrow heads) and physiologic bowel activity (asterisk). Following chemotherapy (b) the primary tumour has significantly reduced in FDG avidity (open arrow). There is now physiologic FDG uptake in brown adipose tissue in the occipital regions (top arrow), supraclavicular regions (middle arrow) and right suprarenal region (bottom arrow), and physiologic bowel activity (asterisk). FDG uptake is also seen in an abdominal lymph node (open arrow) and groin lymph nodes (closed arrow) considered to be due to reactive or inflammatory change, and along an inflamed esophagus.

The EANM Technologists' Guide provides a practical foundation for further education on reconstruction techniques and advances in PET/ CT imaging [14].

See Table 1 for a quick reference and see Figure 1 for an example of selected normal variants.

If problems are discovered after image acquisition, post-processing adjustments can eliminate the need for re-imaging. Techniques include generating new reconstruction data (reconstruct list mode data if acquired), excluding artefacts by limiting the post-processing field of view (FOV) for targeted smoothing, careful realignment of fused images between PET and CT, and rechecking NAC PET for attenuation-driven artefacts. Where reprocessing alters timing or filters, note that SUVs are not directly comparable; if diagnostic stakes remain high, re-imaging can occur with a limited focused bed FOV rather than a full repeat. After these steps, the images need to be interpreted with paediatric physiology in mind.

Table 2 summarises common normal variants and pitfalls in [¹⁸F]FDG PET.

Bladder considerations

Bladder management is an important consideration due to the physiological renal excretion of PET tracers and the potential for concentrated urine to cause significant image artefact, particularly in the pelvis and lower abdomen. Children should be encouraged to empty their bladder immediately before the scan, and nappies should be checked and changed just prior to positioning to prevent contamination or attenuation from a saturated nappy. In infants and young children, ensuring adequate hydration helps reduce urinary concentration, thereby improving image quality and reducing radiation dose to the bladder.

When bladder activity interferes with image interpretation, such as during assessment of pelvic lymph nodes, bladder masses, or adjacent soft tissues, several strategies may be considered. These include the use of IV hydration before and during the uptake phase, post-void or post-catheterisation imaging of selected regions, and, in carefully chosen cases in consultation with the referring clinician, the administration of furosemide to reduce

Findings and Pitfalls	Typical appearance in children	Technologist Actions	Notes for reporting clinician
Thymus (normal variant)	Triangular/sail-shaped anterior mediastinal tissue; homogeneous mild-moderate uptake	Confirm symmetry and benign CT morphology; avoid unnecessary repeats	Appearance consistent with physiologic thymus
Brown adipose tissue (BAT) (normal variant and pitfall)	Symmetrical uptake in the neck, supraclavicular, and paraspinal regions ± mediastinal fat	Keep child warm upon arrival; low-stimulus uptake environment; in some centres, beta-blockers or benzodiazepines may be administered as per local policy	Document warming measures adopted and any medication taken with timing (practice varies internationally)
Growth plates (normal variant)	Bilateral linear physeal uptake at long-bone physes, most prominent during growth spurts	Ensure coverage demonstrates bilaterality and expected distribution patterns to avoid patient recall	Symmetrical physeal uptake expected, based on age
Brain development (normal variant)	Higher cortical uptake in younger children; age-related patterning	Maintain consistent uptake time, recognise age-related cerebral uptake when imaging head & neck patients	Age-appropriate cortical uptake pattern
Physiological organ activity	Symmetrical tonsils and adenoidal uptake; variable bowel uptake; kidneys and collecting system activity; prominent bladder activity	Prompt voiding before positioning; check for contamination	Record voiding time relative to acquisition
Muscle uptake (pitfall)	Increased tongue, strap muscle, and intercostal uptake due to talking, chewing, crying, or shivering	Keep uptake time quiet, warm, low-stimulus; coach using ONE VOICE; rehearse stillness	Note events during uptake (e.g. crying, shivering)
Injection extravasation (pitfall)	Focal activity at cannula site; altered regional biodistribution and inaccurate SUV measurements	Confirm cannula patency pre-injection; immobilise limb; if this occurs, annotate clearly	Record site, extent, timing; caution on regional SUVs
Arms-down attenuation and truncation (pitfall)	Attenuation and truncation artefacts in the thorax or upper abdomen when arms cannot be raised	If arms-down is unavoidable, adapt CT and flag in notes	Arms-down; attenuation correction artefacts possible, CT adapted accordingly
Deviations in dose, timing, and reconstruction parameters (pitfall)	SUV inconsistency vs prior or across beds	Keep uptake time & reconstruction standardised; if changed, annotate	Record dose (including residual activity), uptake time, and reconstruction parameters to ensure comparability

Table 2. Paediatric [¹⁸F]FDG PET – normal variants, pitfalls, and technologist actions.

urinary tracer concentration. These measures help minimise artefacts and improve delineation of pathology. This approach supports optimal diagnostic accuracy while maintaining patient comfort and minimising repeat imaging.

OTHER DIAGNOSTIC RADIOPHARMACEUTICALS

The table below summarises common paediatric PET radiotracers in clinical use at the time of publication. Additional discussion of these and emerging radiotracers is provided in Chapter 4.

Radiopharmaceuticals	Common Indication	Advantages	Disadvantages
[¹⁸ F]FmFBG	Neuroblastoma and other neuroendocrine tumours (NETs)	<ul style="list-style-type: none">» Detects far more lesions than [¹⁸F]FDG and [¹²³I]I-mIBG» Shorter scan time, often no sedation required» Higher tumour-to-background ratio and spatial resolution	<ul style="list-style-type: none">» Limited availability» Requires a new scoring framework – Curie scoring not suitable [15–18]
[⁶⁸ Ga]Ga-DOTA-TATE	Neuroblastoma and other neuroendocrine tumours (NETs)	<ul style="list-style-type: none">» Best for somatostatin receptor (SSTR)-positive NETs.» High lesion contrast and sensitivity» Companion diagnostic tracer for [¹⁷⁷Lu]Lu-DOTA-TATE radionuclide therapy, for identifying receptor-positive candidates	<ul style="list-style-type: none">» Variable SSTR expression in neuroblastoma [16]
[¹⁸ F]FDOPA	Neuroblastoma and other neuroendocrine tumours (NETs)	<ul style="list-style-type: none">» Targets catecholamine synthesis, so biologically well suited for neuroblastoma imaging» Can help select patients for metabolic pathway-targeted research	<ul style="list-style-type: none">» Limited efficacy in aggressive or de-differentiated disease [16]
	Congenital hyperinsulinism (CHI)	<ul style="list-style-type: none">» Distinguishes between focal and diffuse pathology» Helps guide surgical approaches	<ul style="list-style-type: none">» Limited availability [19]
[¹²⁴ I]Iodide	Thyroid cancer	<ul style="list-style-type: none">» Enables pre-therapeutic dosimetry» Useful for assessing iodine-avid metastatic disease» Multiple time point imaging for dosimetry purposes	<ul style="list-style-type: none">» Limited availability» Higher patient radiation dose» Longer half-life means longer scan times [20]
[¹⁸ F]FET	Primary brain tumours including gliomas	<ul style="list-style-type: none">» Provides improved tumour delineation and diagnostic accuracy» Provides reliable differentiation of tumour recurrence vs treatment-related changes, especially in distinguishing true tumour progression from pseudo-progression and radionecrosis	<ul style="list-style-type: none">» Limited availability and regulatory approval [21]

CONCLUSION

PET/CT is a cornerstone modality in paediatric imaging, supporting diagnosis, staging, restaging, and treatment response assessment. Its ability to provide whole-body coverage with quantitative metabolic information underpins timely and accurate clinical decision-making. Technologists play a pivotal role in ensuring high-quality studies through meticulous preparation, child-centred communication, optimised scan acquisition, and consistent post-processing. As technology advances, PET/CT will remain integral to delivering precise, safe, and effective care while promoting child and family-centred practice.

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3.3

Achieving Diagnostic Confidence in Paediatric PET/MR – Technical and Procedural Challenges

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EXECUTIVE SUMMARY

This chapter focuses on paediatric PET/MR imaging with 2- ^{18}F FDG and highlights key considerations for ensuring consistent and reliable imaging. Patient preparation may vary depending on the clinical indication (e.g. oncological, inflammatory or brain imaging), in accordance with European Association of Nuclear Medicine guidelines. Effective coordination among all staff members is essential to maintaining standardised workflows and reproducible results. Particular emphasis is placed on patient comfort and clear communication with both the child and their caregiver, as long acquisition times, acoustic noise and positioning directly influence patient cooperation and motion. The chapter also underscores the importance of routinely verifying the attenuation map (map/MRAC), as segmentation errors, truncation, and hardware or coil-related issues may significantly affect PET image quality and quantification. Finally, protocol optimisation is discussed, focusing on balancing scan time, SAR (specific absorption rate) limitations and sequence selection to ensure feasible diagnostic examinations while preserving image quality and consistency in follow-up studies.

Keywords: Paediatric; Diagnostic Confidence; Attenuation Correction; MR-based Attenuation Correction; Motion Management; Motion Correction; Sedation; PET/MR; Hybrid Imaging.

INTRODUCTION

The progressive adoption of positron emission tomography with magnetic resonance (PET/MR) as a hybrid imaging modality has generated growing interest among technologists, owing to both its technological features and its operational implications. Although its dissemination remains less widespread overall than positron emission tomography integrated with X-ray computed tomography (PET/CT) systems, PET/MR represents a high-value platform that requires solid competencies and highly specialised training for professionals working directly in this field. For the purpose of this chapter, the discussion is limited to paediatric examinations performed using 2- ^{18}F FDG. The potential of PET/MR is particularly relevant in the paediatric setting, as it may replace PET/CT within follow-up pathways and reduce overall radiation exposure by eliminating the CT component. In parallel, the high soft-tissue contrast and multiparametric imaging capabilities of MR—including whole-body diffusion-weighted imaging (DWI), a functional technique sensitive to tissue cellularity—provide tangible benefits for disease characterisation and longitudinal surveillance [1]. Paediatric 2- ^{18}F FDG PET/MR is a highly complex procedure because it combines, within a single diagnostic act, the stringent constraints and requirements associated with high-field MRI (workflow organisation, MR safety, and the need to control patient motion) with examination times that may be substantially longer than those used in PET/CT [1]. This combination often necessitates structured approaches to patient preparation and management, including immobilisation and, where appropriate, sedation or anaesthesia, as

well as continuous monitoring and close multidisciplinary collaboration [1,2]. In children, diagnostic quality also depends to a considerable extent on appropriate preparation and pathway standardisation; in particular, for 2- ^{18}F FDG studies, patient preparation (including measures aimed at reducing biological variability and artefacts) is a recognised determinant of image quality and interpretative accuracy [3]. Within this framework, the adoption of tailored communication strategies together with clear role allocation within the team contributes to improved tolerability, cooperation, and procedural safety in paediatric practice [2].

Historical development of PET/MR hybrid imaging

In 1997, the feasibility of truly simultaneous PET/MR acquisition was demonstrated using scintillation detectors placed near the MR receive coil, with scintillation light routed via optical fibres to photomultiplier tubes located outside the high-field region, addressing the incompatibility of PMTs with the MR environment [4]. However, this solution was complex and difficult to scale, remaining largely a proof-of-concept [4]. Subsequently, system-level solutions shifted toward solid-state detectors such as avalanche photodiodes (APDs), which are far less sensitive to static magnetic fields; high-field testing supported their compatibility and enabled integrated small-animal PET/MR prototypes, consolidating simultaneous PET/MR imaging in the mid-2000s [5,6]. In clinical neuroimaging, APD-based PET inserts for 3T MRI further enabled high-resolution simultaneous acquisitions [7,8]. In parallel, sequential approaches were implemented using

adjacent scanners and dedicated patient transfer systems to ensure reproducible co-registration [9]. Fully integrated whole-body PET/MR systems were introduced in clinical research settings around 2010 and subsequently obtained regulatory clearance; PET performance and the feasibility of PET/MR co-acquisition were subsequently demonstrated through standardised testing [10–12]. The adoption of silicon photomultipliers (SiPMs), including digital variants, enabled practical time-of-flight PET/MR, improving timing performance and supporting more robust image quality and quantification [13,14].

PET/MR site specifics and general background

In fully integrated PET/MR systems, the PET detector ring is integrated within the MR system, enabling truly simultaneous acquisitions. Access to the magnet room is generally defined by a dual-barrier layout: a first closure ensuring continuity of the RF (radio frequencies) shielding provided by the Faraday cage [15], and a second door—often sliding and always shielded—designed to meet the radiation protection requirements as per local area classification (controlled or supervised), in the presence of the 511 keV annihilation photons associated with the PET component.

A PET/MR site requires a structural set-up that integrates the needs of nuclear medicine with those of MR. From an engineering and facility perspective, the hybrid system is embedded within a functional area that includes uptake rooms, the scanner room and a technical equipment room, in addition to the usual radiopharmaceutical injection rooms. These areas must be clearly identified and

accessible only to appropriately trained staff and to patients who have undergone MR screening (i.e. completion of a safety questionnaire and informed consent). The pathway into the MR safety area, defined as areas where the static magnetic field B_0 is ≥ 0.5 mT (5 Gauss), also includes a systematic check for MR contraindications, including the use of ferromagnetic detection gates. Surface body coils in a phased-array configuration are used to improve MR image quality, as they enable signal reception with a high signal-to-noise ratio (SNR) in regions near the coil by efficiently combining the input from multiple receiver elements [16].

In the PET/MR context, when coils lie within the PET field of view, their presence must be modelled in attenuation correction to preserve quantitative accuracy [17]. Coil weight also varies by model; manufacturer-declared values may range from approximately 1–2 kg for anterior body coils to higher values for rigid head/neck coils, requiring particular care during handling and positioning, both for operator safety and to ensure patient stability and comfort during prolonged acquisitions.

The overall structural set-up is completed by the technical room, which houses the cryogenic systems used to cool the MR component, including magnet monitoring systems and the dedicated compressor unit. According to the manufacturer's documentation, this area also contains the main system electronics cabinets, including the RF amplifier, gradient cabinet, system control cabinet, and cabinets dedicated to the PET component. These are complemented by PET acquisition/continuity racks (e.g. ACS, PRS and UPS), cooling systems, machine electrical panels (protection and distribution), and facility monitoring and safety devices (technical

alarms and environmental sensors specified in the site design).

PAEDIATRIC PET/MR SETTING: CHALLENGES AND PRACTICAL TIPS

The paediatric population is defined as patients aged from birth to 18 years of age (up to, but not including, 18-year-olds) [18]. For this group, PET/MR acquisition is performed within a dedicated setting which, in addition to general structural requirements, must also take account of specific clinical, organisational, and technical factors. Appropriateness of and justification for the examination are assessed by the nuclear medicine physician, involving the radiologist and the referring specialist where needed; at this stage, the most suitable approach—awake imaging versus sedation—is also determined, considering age, weight, developmental maturity, and the compliance of both the patient and their family. Once the procedure has been defined, it is essential to provide timely, specific instructions to the patient, where appropriate, and/or their caregivers for the hours leading up to the injection of 2- ^{18}F FDG. Exposure to cold temperatures may activate brown adipose tissue (BAT), resulting in uptake in supraclavicular, paravertebral and mediastinal regions, which can be mistaken for pathological lymph nodes and may compromise PET image quality and interpretation [19].

Upon arrival at the department, the child and their caregivers are welcomed in an environment designed to reduce emotional arousal and promote cooperation. The family members play a central role here: their involvement is crucial to establishing the child's trust in the staff. It is therefore

important to invest time and effort in building a solid relationship, minimising communication barriers, and addressing concerns, requests for information, and the need for reassurance.

The procedure is explained clearly to parents/caregivers, both when sedation is planned and when imaging is performed with the child awake and only partially cooperative [2]. A key step in the workflow is venous access placement, performed by trained staff, as it affects both the reliability of radiopharmaceutical administration and the continuity of the procedure in an examination that is long and logistically complex. Venous access is checked and secured with particular care (patency, fixation, site protection), also in view of the risk of extravasation and its consequences for image quality/quantification and examination repeatability. Prior to radiopharmaceutical administration, glycaemia should be checked and appropriate fasting ensured according to patient age and clinical conditions, in line with 2- ^{18}F FDG PET/CT protocols as recommended by the EANM guidelines. After venous preparation, 2- ^{18}F FDG is administered according to the centre's own guidelines and local radiation protection procedures. In paediatric patients, administered activity should be scaled according to body weight or body surface area in accordance with the EANM Paediatric Dosage Card (2016), in order to ensure an optimal balance between image quality and radiation exposure. Practical implementation of these recommendations is supported by the SNMMI Paediatric Dose Calculator (available online or as a stand-alone application), which provides standardised weight-based

activity calculation and an estimate of the associated radiation exposure.

This is followed by the uptake phase in a controlled environment, during which the nuclear medicine professionals play a pivotal role in providing continuous assistance to the child and in supporting the caregivers: clinical monitoring, comfort management (thermal and psychological?), minimisation of unnecessary stimuli, and surveillance of the venous access.

At the end of the uptake period, the patient is invited to empty their bladder and is then welcomed by the nuclear medicine technologist in the MR access area following a thorough explanation of how the examination will proceed using simple language and age-appropriate terminology. The explanation is not merely informative but is also a request for cooperation: it includes breathing instructions (when required by the local protocol), anticipates expected sensations (vibration, noise, duration, the need to remain still, and a possible sensation of warmth), and provides an overview of coil positioning. From a technical standpoint, the MR system configuration and the available coils may pose additional challenges: the weight and bulk of surface coils must be compatible with the child's body size and with maintaining a comfortable, stable position, while avoiding excessive compression and interference with venous access or monitoring devices. Particular attention is also given to how the call device is introduced: to reduce anxiety, it is not described as an "alarm" but rather as a "bell/button to call us", reinforcing the child's perception of control and safety. With regard to acoustic protection, it should be borne in mind that the use of over-ear MR-compatible headphones in PET/MR brain

scans may cause measurable attenuation of 511 keV photons and introduce bias in PET quantification if not appropriately managed; therefore, consideration should be given to alternative solutions or corrective strategies compatible with the system and acceptable to the child [20]. In sedated patients, radiotransparent MR-compatible foam supports of different heights are used to position surface body coils; the technologist selects the appropriate support size in collaboration with the anaesthesiologist to maintain sufficient clearance over the thorax and abdomen, allowing adequate respiratory excursion while preserving receive sensitivity compatible with image quality. At the same time, the technologist verifies appropriate routing of lines and devices (e.g. infusion systems, monitoring leads, coil connectors) near the coils, ensuring stability and preventing interference with table motion, and confirms that all equipment used is compatible with the MR environment [22]. An additional level of complexity arises from the presence of a caregiver, which may be permitted in selected cases when the examination is performed in awake mode. Whether or not to allow a parent (or accompanying person) into the acquisition room must be evaluated by balancing the psychological benefit to the child against MR safety and radiation protection constraints. The caregiver must undergo MR safety screening and the compatibility checks required for access to the PET/MR room; a dedicated informed-consent form describing risks and behavioural rules is also mandatory [22]. From a radiation protection perspective, caregiver exposure during the procedure must be carefully considered, particularly for prolonged examinations, in accordance with the ALARA principle [21]. This can

be achieved, for example, by having the caregiver stand as far away from the patient as tolerable—aiming, of course, to achieve the maximum distance between them while still ensuring the child's collaboration. This underscores the need for an integrated and well-coordinated team approach, with more dedicated time than in adult practice for reception, preparation, anxiety management and comfort verification, alongside protocol time optimisation and adherence to MR safety standards for both the child and the accompanying person [2,21,22]. Finally, the environmental setting plays a crucial role: spaces and pathways should be as child-friendly as possible, with personalised environments and distraction strategies that reduce anxiety, facilitating both awake examinations and efforts to avoid or limit sedation [2].

ACQUISITION OPTIMISATION: TRADE-OFFS BETWEEN IMAGE QUALITY, SPECIFIC ABSORPTION RATE, AND TOLERABILITY

This section refers to an integrated clinical 3T PET/MR system using avalanche photodiode (APD) PET detectors (non-TOF), coupled with a dedicated software environment supporting both PET and MR acquisition and reconstruction. From a PET acquisition perspective, data can be recorded either in list mode or in sinogram mode (with pre-binning of events into projections). In list mode, each coincidence event is stored individually, preserving access to raw data and enabling, where needed, greater flexibility during reconstruction (e.g. reframing, synchronisation/gating, and handling of

motion-degraded time intervals), whereas the sinogram represents an aggregation of counts into a representation more directly suited to reconstruction [24]. In the paediatric setting, whole-body and brain examinations are acquired in list mode to maintain maximum control over the reconstruction process and motion management [24].

In paediatric PET/MR, the acquisition phase is a high-complexity step: diagnostic-quality results depend on achieving a balance between technical performance, safety, and examination tolerability. In this context, the technologist plays a pivotal role in “real-time” optimisation of scanning strategies, adapting protocols and parameters to the child's condition and to the constraints of the MR environment. A critical aspect is the management of the specific absorption rate (SAR), which may be perceived as a sensation of warmth, particularly in sequences with high energy deposition (e.g. TIRM/STIR and, more generally, sequences with a high RF burden) [25]. Operationally, this is addressed through targeted technical choices: increasing TR (to distribute RF power over time), reducing flip angles, and optimising parallel imaging (iPAT), which—when appropriately implemented—can accelerate acquisition and reduce part of the sequence burden [25]. This optimisation is complemented by selecting the appropriate respiratory strategy (free breathing, breath-holding if possible, and, where applicable, gating) for the individual patient to keep artefacts and repeat scans to a minimum. Scanning likewise requires continuous monitoring, made more challenging by the fact that paediatric patients are covered by coils, with inevitably limited physical access; as a consequence, interaction and

assessment of clinical and behavioural status are primarily effected from outside the room through observation and targeted communication, while minimising unnecessary stimuli. An additional aspect, typical in paediatric practice, is that certain physical sensations generated during MR acquisition may promote spontaneous sleep: perceived warmth (more likely during high-RF sequences) and vibrations (more evident during sequences with rapid gradient switching, such as DWI) may induce relaxation, leading to sleep. This phenomenon is generally positive and sometimes advantageous because it reduces anxiety and voluntary motion; however, sudden awakenings may trigger abrupt head movements of the patient due to transient confusion or disorientation, with a risk of impact against the coils, particularly when using the rigid head/neck coil. This underscores the importance of a “protected” set-up with appropriate MR-safe padding and gentle head support (without restraint), as well as clear pre-defined team roles to ensure prompt intervention in case of abrupt behavioural changes. Overall, successful paediatric PET/MR scanning depends not only on a theoretically “optimal” protocol, but on the team's ability to keep the patient-coil-sequence-monitoring system stable and to intervene competently in the presence of discomfort, motion, or instability. This is also highly relevant for the PET component: in integrated systems, the accuracy and robustness of quantification depend closely on positional stability and on the overall quality of the acquisition workflow [23].

DIAGNOSTIC CONFIDENCE: THE CONTRIBUTION OF MRI TO PET/MR

In paediatric whole-body FDG PET/MR, TIRM/STIR (hereafter, TIRM) and DWI are particularly informative MR sequences because they provide additional characterisation beyond PET alone. TIRM/STIR, typically implemented with a long TR, is a fat-suppressed T2-weighted sequence sensitive to oedema and osteomedullary abnormalities; therefore, it may contribute to identifying extranodal and bone marrow involvement and provide anatomical context for FDG-avid foci. In the presence of PET uptake, a concordant TIRM finding (fat-suppressed T2 hyperintensity) increases diagnostic confidence, particularly when the abnormality is osteomedullary—for instance, focal marrow hyperintensity, oedema, and signal heterogeneity consistent with lymphomatous involvement, which provide morphological support for the 2-^[18F]FDG focus. Conversely, when uptake is borderline or located in regions with variable physiological background activity, TIRM helps discriminate findings: for example, the absence of structural abnormalities in bone segments or soft tissues reduces the likelihood that the uptake represents disease. For lymph nodes, however, TIRM alone is less specific (reactive nodes may also appear hyperintense), which is why integration with DWI/ADC becomes crucial to consolidate interpretation.

When PET and DWI provide concordant information at the same site, interpretative confidence increases, particularly for small lesions or in complex anatomical districts and in situations where 2-^[18F]FDG PET may be limited by false positives (e.g. inflammation) or false negatives (low-

uptake lesions). In FDG-avid lymphomas, staging and response assessment are formally based on PET criteria (Lugano/Deauville) [26,27]; however, recent paediatric studies report moderate-to-good agreement between PET-based and WB-DWI-based assessments (including quantitative biomarkers such as ADC), albeit with a degree of discordance that limits the systematic replacement of PET/CT [28].

Within this framework, the high informational contribution of the TIRM + DWI combination may support paediatric PET/MR protocols that prioritise the selective use of gadolinium, reserving contrast administration for cases in which a meaningful additional clinical benefit is expected. In paediatric brain imaging, 2-^[18F]FDG PET/MR is very valuable in epilepsy evaluation, particularly when the goal is to increase diagnostic confidence in identifying the epileptogenic focus. In this context, MR—through dedicated morphological characterisation—enhances the ability to recognise abnormal cortical patterns (e.g. focal cortical dysplasia) and to better define their extent and anatomical relationships. PET with 2-^[18F]FDG adds metabolic information (typically interictal hypometabolism), while a distinctive feature of PET/MR is the simultaneous acquisition of both anatomical and physiological components: this reduces mismatches related to positioning and patient condition, improves co-registration, and makes localisation of the metabolic pattern relative to the anatomical correlate more reliable. In summary, simultaneous PET/MR acquisition and the integration of metabolic information with morphological characterisation are key factors in increasing diagnostic confidence in children with epilepsy, especially within the pre-surgical pathway.

MRAC AND μ -MAP: ARTEFACTS AND SOLUTIONS

In paediatric PET/MR, the attenuation map (μ -map) derived from MR-based attenuation correction (MRAC) sequences (e.g. Dixon or ultrashort echo time, UTE) is one of the main sources of quantitative variability and artefacts, as attenuation at 511 keV is estimated from MR data and vulnerable to imperfect segmentation, spatial mismatch, and field-of-view (FOV) limitations [29]. In the whole-body setting, a typical operational pattern is a μ -map with an inconsistent body contour or with structures appearing “outside” the profile (e.g. the spine/vertebral column outside the contour), frequently associated with micro-movements, changes in respiratory pattern between MRAC and PET, suboptimal centring, and, most importantly, truncation/distortion artefacts at the edges of the MRI FOV, with the potential introduction of clinically relevant bias in the attenuation-corrected PET images [31]. Practical management includes systematic verification of the μ -map/MR overlay and, where useful, comparison with non-attenuation-corrected PET images; in the case of an obvious error, the patient is repositioned/immobilised and the MRAC acquisition is repeated, along with the application of FOV-extension/truncation-correction strategies where available [31].

If the “bone” component is clearly erroneous or misaligned, reconstruction with a μ -map without bone may be a pragmatic solution to avoid larger errors introduced by an unreliable bone map, while documenting the choice and the expected impact [29]. In brain imaging, another recurrent pattern is UTE with radial “star-like” artefacts, which can result in

an unstable cranial μ -map due to air/bone misclassification, with effects that are most pronounced near the calvarium and skull base. Operationally, repeating the UTE acquisition is recommended; if the artefact persists and compromises the bone map, reconstruction with a bone-free μ -map (Dixon) may be adopted as a “salvage” option, bearing in mind the potential underestimation in regions adjacent to bone [33]. Finally, in systems without TOF, the impact of MRAC errors tends to be more pronounced; where available, TOF information can reduce (at least in part) quantitative errors induced by an imperfect MRAC [34].

PAEDIATRIC PET/MR EXAM VS. PAEDIATRIC PET/ CT SCAN

In the paediatric population, PET/CT is often preferred when a fast and robust examination is required, providing reliable CT-based attenuation correction and superior assessment of the pulmonary findings, including small nodules and calcified lesions, which may reflect not only oncological disease but also benign, infectious or inflammatory conditions; this reduces the risk of artefacts related to limited patient cooperation and motion challenges. 2-^[18F]FDG PET/MR becomes particularly strategic in paediatric practice when the aim is to reduce cumulative radiation exposure during follow-up pathways and to leverage superior soft-tissue characterisation (brain, liver, pelvis, bone marrow) through dedicated multiparametric sequences (e.g. DWI). However, in children PET/MR is more prone to operational challenges: longer examination times, a higher likelihood of micro-movements, and a MRAC approach

that is more vulnerable to artefacts (e.g. truncation, suboptimal body μ -maps, or degraded UTE in brain imaging). This makes careful protocol planning and systematic quality control of attenuation maps and reconstructed images essential.

CONCLUSION

Paediatric FDG PET/MR remains a high-clinical-value imaging modality when the goal is to integrate PET metabolic information with MR multiparametric characterisation, while maintaining an approach that is attentive to cumulative radiation exposure within follow-up pathways. Diagnostic quality depends not only on technology, but above all on the ability to manage an intrinsically complex examination: prolonged scan times, the need for immobility, MR safety requirements, continuous monitoring, and relationship management with the young patient and their family. Within this balance, the technologist acts as a true “director” of the process, as real-time optimisation (sequences, SAR, breathing strategy, comfort) and quality control (μ -map/artefacts) determine examination reliability and reproducibility.

This complexity translates into an unusual level of commitment for the entire team, both organisationally and in terms of psycho-physical workload, requiring constant attention, coordination, and adaptability throughout all phases of the examination. At the same time, when the study is successfully completed and yields clinically robust information, the pathway is highly rewarding for the professionals involved, as it tangibly underlines the value of multidisciplinary collaboration and technical-procedural accuracy.

A further, equally important objective is that the paediatric patient and their family complete the PET/MR diagnostic pathway with a positive overall experience, perceiving the examination as manageable and safe, without feelings of fear or trauma. This outcome largely depends on the quality of reception, assistance, communication and comfort provided throughout all stages of the diagnostic process. Looking ahead, the development of paediatric PET/MR may benefit from innovations that further reduce operational barriers.

A priority area concerns MR coils, which should evolve toward lighter, less bulky solutions with more integrated and patient-friendly designs, to facilitate positioning, improve comfort, and reduce factors that limit access to the patient during scanning. In parallel, reducing overall examination time remains a key objective, both through more streamlined yet diagnostic protocols and through parameter optimisation and fast sequences. Finally, improvements in detector performance and acquisition electronics may increase sensitivity and quantitative robustness, thereby supporting strategies to reduce administered activity—an aspect particularly relevant in paediatric pathways and follow-up imaging.

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Diagnostic Radiopharmaceuticals — Promising Agents

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EXECUTIVE SUMMARY

Paediatric nuclear medicine is entering a period of rapid transformation driven by advances in molecularly targeted radiopharmaceuticals. Traditional agents such as [^{18}F]FDG PET/CT continue to serve as the backbone for evaluating disease burden and glucose metabolism; however, they are increasingly complemented by novel tracers targeting specific biological pathways. Imaging development is constrained by heightened radiation safety concerns, ethical and regulatory restrictions, and limited commercial incentives.

This chapter reviews emerging diagnostic radiopharmaceuticals with growing relevance to paediatric imaging, emphasising molecular targets, clinical applications, advantages, and limitations. Tracers reviewed include: [^{18}F]mFBG, [^{11}C]mHED, [^{124}I]mIBG, [^{18}F]FDOPA, [^{18}F]FLT, [^{68}Ga]Ga-FAPI, [^{68}Ga]Ga-PentixaFor, [^{64}Cu]Cu-dinutuximab beta, [^{89}Zr]Zr-bevacizumab, and [^{89}Zr]Zr-trastuzumab. Future progress will depend on paediatric-specific tracer development, multi-centre validation, and harmonised regulatory pathways.

Keywords: novel radiopharmaceuticals; paediatric imaging; emerging; molecular imaging; promising; theranostics

INTRODUCTION

The development of novel radiopharmaceuticals for paediatric imaging is challenged by biological differences between children and adults, heightened radiation safety concerns, ethical and regulatory constraints, and limited economic incentives [1, 2]. Conventional agents such as [^{18}F]FDG PET/CT remain central to paediatric imaging but show

suboptimal diagnostic performance in common paediatric conditions including neuroblastoma and gliomas. Molecularly targeted radiopharmaceuticals are therefore being developed to complement [^{18}F]FDG by evaluating specific biological pathways and receptor systems relevant to prognosis, therapeutic decision-making and response assessment, supporting precision imaging and the expanding integration of diagnostic imaging with theranostic treatment strategies. This chapter reviews selected emerging radiopharmaceuticals, highlighting their molecular targets, clinical applications, strengths, limitations, and their evolving role in paediatric nuclear medicine.

THE ROLE OF [^{18}F]MFBG (META- ^{18}F]FLUOROBENZYLGUANIDINE)

Meta- ^{123}I iodobenzylguanidine (^{123}I]mIBG) SPECT/CT remains a cornerstone of paediatric neuroendocrine imaging in neuroblastoma, paraganglioma, and pheochromocytoma, enabling standardised tumour burden assessment using Curie and SIOPEN scoring; however, its clinical utility is limited by prolonged multi-day protocols, thyroid blockade requirements, lower spatial resolution, and frequent sedation requirements [1]. Meta- ^{18}F fluorobenzylguanidine (^{18}F]mFBG) preserves the same norepinephrine transporter targeting while offering the significant technical advantages of PET/CT, and will likely replace [^{123}I]mIBG in the future [1, 3]. Clinical studies demonstrate superior detection of osteomedullary, nodal, and intraspinal disease, producing higher Curie and SIOPEN scores that reflect increased lesion sensitivity rather than true differences in tumour biology [4, 5]. In the prospective evaluation (NCT02348749) by Pandit-Taskar

et al. (2025), dosing was normalised to adult body surface area at a maximum of 296 MBq (8 mCi), administered as a 1-minute intravenous bolus without fasting or pre-medication [5].

Figure 1 demonstrates the biodistribution of [^{123}I]mIBG compared to [^{18}F]mFBG.

Advantages:

» Biodistribution similar to [^{123}I]mIBG with faster tissue uptake and renal clearance

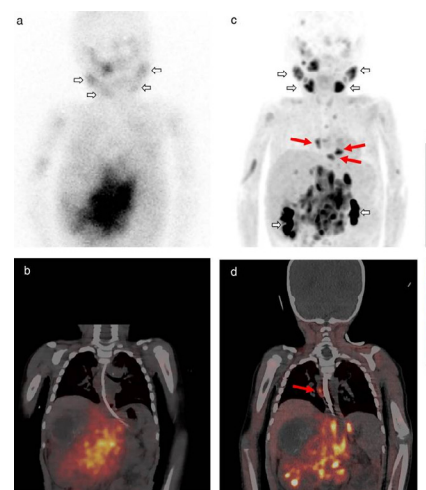


Figure 1. (a) Planar [^{123}I]mIBG scintigraphy and (b) fused SPECT/CT and (c) corresponding [^{18}F]mFBG PET maximum intensity projection (MIP) and (d) fused PET/CT. Short arrows indicate physiological uptake (salivary glands and pelvic/colic system). Long arrows indicate additional mediastinal lymph node metastases detected on [^{18}F]mFBG PET/CT but missed on [^{123}I]mIBG scanning [3]. Reproduced from Samim et al. [3] with permission.

» Same-day imaging with superior spatial resolution, shorter acquisition times, decreased sedation requirements, and elimination of thyroid blockade [5]

» Acquisition at 1–2 hours post-injection versus up to 24 hours for [^{123}I]mIBG [3]

» Quantitative SUV assessment supports objective tumour activity and treatment response monitoring [5]

» May improve staging accuracy and enable earlier detection of recurrent or progressive disease, with additional lesions potentially guiding biopsy for diagnostic confirmation and molecular analysis [5]

Disadvantages:

» No marketing authorisation; remains investigational

THE ROLE OF [^{11}C]MHED (META-HYDROXY- ^{11}C]EPHEDRINE)

[^{11}C]mHED is a hydrophilic norepinephrine analogue rapidly internalised via the norepinephrine transporter, accumulating in neural crest-derived tumours [6]. First described in neuroblastoma by Shulkin et al. (1996) and validated by Franzius et al. (2006), direct comparative studies report equivalent diagnostic performance to [^{123}I]mIBG scintigraphy, with similar sensitivities (99% vs. 93%) and identical specificity (100%) [6].

Advantages:

» Short 20.4-minute half-life results in reduced radiation dose relative to [¹²³I]mIBG scintigraphy [6]

» Imaging within 0–30 minutes post-injection; simplified single-day workflow with reduced sedation requirements and no thyroid blockade [6]

Disadvantages:

» Requires on-site cyclotron and immediate post-synthesis imaging, limiting routine implementation [6]

» Higher mean positron range in water (~3.6 mm for [¹¹C] vs. ~0.6 mm for [¹⁸F]) may result in inferior spatial resolution

» No marketing authorisation

THE ROLE OF META-[¹²⁴I] IODOBENZYLGUANIDINE ([¹²⁴I]MIBG)

[¹²⁴I]mIBG shares the same norepinephrine transporter targeting mechanism as [¹²³I]mIBG and [¹³¹I]mIBG, but the iodine-124 label (half-life 4.2 days) enables PET acquisition, conferring superior spatial resolution and true quantification [7]. Its biodistribution mirrors [¹²³I]mIBG, allowing established Curie and SIOPEN scoring systems to be applied directly [7]. Cistaro et al. (2015) first reported its use in two paediatric patients with metastatic neuroblastoma, detecting more osteomedullary lesions than conventional scintigraphy [8]. A subsequent first-in-humans study demonstrated superior lesion detection compared to [¹²³I]mIBG planar imaging and SPECT/CT, with higher Curie scores, particularly in the chest, spine, head and neck, and extremities

[9]. Its most clinically distinctive role is in pre-therapeutic dosimetry for [¹³¹I]mIBG therapy: patient-specific dosimetry using pre-therapy [¹²⁴I]mIBG dynamic PET/CT is feasible for estimating organ and tumour absorbed doses, with dosimetry-guided therapy achieving high tumour doses within acceptable toxicity thresholds [10].

Advantages:

» Superior spatial resolution and true quantitative capability compared to [¹²³I]mIBG SPECT [7, 9]

» Long half-life permits serial imaging and patient-specific dosimetry planning for [¹³¹I]mIBG therapy [9, 10]

» Compatible with established Curie and SIOPEN scoring systems [7]

» Theranostic pairing with [¹³¹I]mIBG therapy using the same molecular target [9, 10]

Disadvantages:

» Effective dose approximately 10–20 times that of [¹⁸F]FDG in the paediatric population; mitigation with low administered activity (1.05 MBq/kg) results in longer acquisition times and reduced image quality [9]

» No established recommended dose or optimal acquisition timing [9]

» Very limited paediatric clinical experience; only small feasibility cohorts reported [7, 9]

» Availability restricted to centres with cyclotron production capability

THE ROLE OF [¹⁸F]FDOPA (6-[¹⁸F]FLUORO-3,4-DIHYDROXYPHENYLALANINE)

[¹⁸F]FDOPA is a radiolabelled amino acid analogue metabolised in catecholamine pathways that crosses the blood-brain barrier, with uptake reflecting amino acid transport and aromatic L-amino acid decarboxylase (AADC) activity rather than glucose metabolism [11]. This results in prominent accumulation in neuroendocrine tissues and enables detection of both high- and low-grade brain tumours independently of blood-brain barrier integrity, complementing MRI [12]. Its principal paediatric indications include tumours of neuroendocrine and neural crest origin (phaeochromocytoma, paraganglioma, and neuroblastoma), brain tumours, congenital hyperinsulinism, and medullary thyroid carcinoma [11–15].

Figure 2 shows intense [¹⁸F]FDOPA uptake in recurrent diffuse intrinsic pontine glioma (DIPG).

Advantages:

» Minimal physiological brain uptake confers superior tumour-to-background

ratios compared to [¹⁸F]FDG for intracranial tumours [12]

» Superior lesion detection compared to [¹²³I]mIBG in paediatric neuroblastoma [13]

» Physiological basal ganglia uptake may partially obscure adjacent lesions in neuro-oncology; however, it can serve as an internal reference for tumour-to-background ratio calculation [12, 16]

» Marketing authorisation supports routine clinical use

Disadvantages:

» Paediatric evidence limited by absence of large multi-centre prospective studies [12]

THE ROLE OF [¹⁸F]FLT ([¹⁸F] FLUOROTHYIMIDINE)

[¹⁸F]fluorothymidine (FLT) is a thymidine analogue that reflects cellular proliferation by measuring DNA synthesis rather than glucose metabolism [18]. In paediatric patients, [¹⁸F]FLT has demonstrated utility in diagnosing high-grade brain tumours and lymphoid malignancies, where uptake

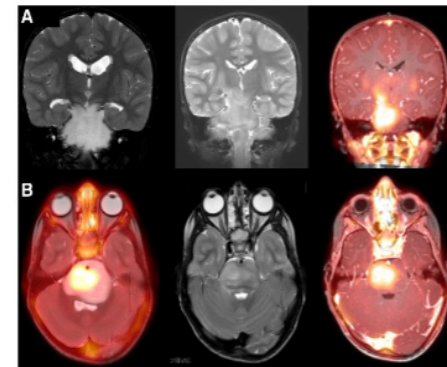


Figure 2. Intense [¹⁸F]FDOPA uptake in recurrent diffuse intrinsic pontine glioma (DIPG) showing better tumour delineation than MRI alone, with intensity of uptake likely a prognostic parameter. (A) From left to right: Coronal T2-weighted fat-saturated initial MR, coronal T2-weighted fat-saturated 9-month follow-up, and coronal [¹⁸F]FDOPA 9-month follow-up PET/MR images. (B) From left to right: Axial [¹⁸F]FDOPA PET fused to initial MR, axial T2-weighted fat-saturated 9-month follow-up MR, and axial [¹⁸F]FDOPA 9-month follow-up PET/MR images [17]. Reproduced from Djekidel et al. [17] with permission.

correlates with tumour grade, proliferative activity, and treatment response, and it shows promise as a biomarker for non-invasive assessment of proliferation in haematological malignancies with correlation to Ki-67 immunostaining [19]. It remains an investigational adjunct rather than a routine clinical tool, pending further prospective validation.

Figure 3 demonstrates the biodistribution of [^{18}F]FLT (a) in comparison to that of [^{18}F]FDG (b).

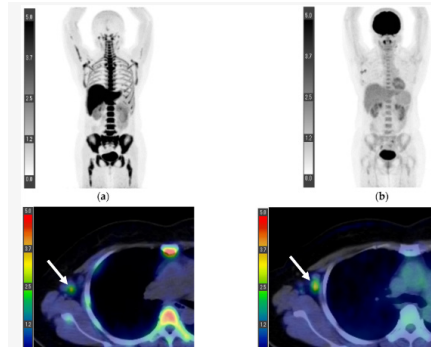


Figure 3. (a) Maximum intensity projection (MIP) of [^{18}F]FLT PET. (b) MIP of [^{18}F]FDG PET. (c) Axial [^{18}F]FLT PET/CT and (d) axial [^{18}F]FDG PET/CT. The axillary lymph node showing greatest accumulation differed between tracers, with SUVmax values of 3.0 and 3.4 respectively (arrows) [22]. Reproduced from Mori et al. [22] with permission.

Advantages:

- » Minimal physiological uptake in normal brain tissue allows clearer visualisation of intracranial tumours compared to [^{18}F]FDG [20]
- » Lower accumulation in areas of inflammation reduces false positives, particularly in lymphoma [20]

Disadvantages:

- » Uptake in reactive lymph nodes and post-chemotherapy thymic hyperplasia may generate false positives, mimicking lymphoma recurrence [20]
- » Cerebral uptake depends on blood–brain barrier disruption and may underestimate low-proliferative lesions [21]
- » High physiological bone marrow uptake limits utility in evaluating bone and marrow disease, particularly in paediatric patients with proportionally greater red marrow volume [19, 20]

THE ROLE OF [^{68}Ga]GA-FAPI

[^{68}Ga]Ga-FAPI targets fibroblast activation protein (FAP), overexpressed by cancer-associated fibroblasts within the tumour microenvironment, demonstrating high tumour-to-background contrast. It has shown broad applicability in adult oncology, though its role in paediatric imaging remains limited [23, 24]. Early paediatric data include a 2025 report by Jenabi et al. of two children with adrenocortical carcinoma where FAPI PET/CT demonstrated superior performance over [^{18}F]FDG in detecting skeletal lesions [26], and a 2022 case report by Zhang et al. demonstrating uptake in a child with aggressive perivascular epithelioid cell tumour [27]. Gliomas show variable FAP expression, though clinical relevance for paediatric midline gliomas has yet to be established [24, 25]. Rapid clearance, favourable dosimetry, and pharmacokinetics make [^{68}Ga]Ga-FAPI well-suited to paediatric use, with future research needed to refine patient selection and explore theranostic applications.

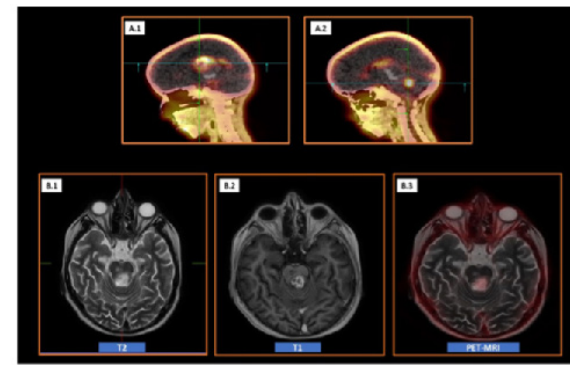


Figure 4. (a) A 6-year-old boy with a low-grade glioma. CT scan reveals a large hyper-vascular soft tissue density mass centered in the left thalamus and pedunculated to the 4th ventricle, with moderate [^{68}Ga]Ga-FAPI uptake. (b) A 13-year-old boy with a low-grade glioma. MRI shows a hyperintense mass lesion arising from midbrain with extension to the 4th ventricle, presenting rim-like thick enhancement and a central non-enhancing area without restriction on DWI, demonstrating mild to moderate [^{68}Ga]Ga-FAPI uptake [25].

Advantages:

- » No fasting, anti-diabetic drug adjustment or exercise restriction required, unlike [^{18}F]FDG [28]
- » Higher lesion detection rates compared to CT and [^{18}F]FDG across multiple tumour types [29]
- » Minimal FAP expression in normal tissues produces very high tumour-to-background ratios [29]
- » Newer FAPI analogues with higher binding affinity further improve lesion detection [29]
- » Theranostic potential through pairing with beta or alpha emitters

Disadvantages:

- » Evidence in paediatric populations remains limited; larger controlled studies needed [29]
- » Role in paediatric midline gliomas uncertain; should be interpreted with caution (Figure 4) [25]

THE ROLE OF [^{68}Ga]GA-PENTIXAFOR

[^{68}Ga]Ga-PentixaFor is a cyclic peptide chemokine analogue to CXCL12 that demonstrates excellent binding to the C-X-C motif chemokine receptor 4 (CXCR4), overexpressed in more than twenty cancer types and associated with tumour aggressiveness, metastatic behaviour, and bone marrow involvement [30, 31]. In paediatric malignancies, elevated CXCR4 expression correlates with adverse prognosis in medulloblastoma, high-risk neuroblastoma with bone and marrow metastases [30], and leukaemia characterised by marrow retention and chemotherapy resistance [30]. Figure 5 illustrates CXCR4-directed PET/CT using [^{68}Ga]Ga-PentixaFor across different solid tumour entities [31].

Advantages:

- » Whole-body assessment of CXCR4 expression to support staging, response evaluation, and selection for CXCR4-directed therapies

» No specific patient preparation is required

» Theranostic potential with [^{177}Lu]/Lu/[^{90}Y] Y-Pentixather [30, 32]

Disadvantages:

» Clinical experience in paediatrics remains limited and largely extrapolated from adult studies

» High physiological uptake in urinary bladder, spleen, and kidneys

THE ROLE OF [^{64}Cu]/Cu-DINUTUXIMAB BETA

[^{64}Cu]/Cu-dinutuximab beta is a radiolabelled anti-GD2 monoclonal antibody targeting the disialoganglioside GD2, overexpressed in neuroblastoma and other paediatric solid tumours including osteosarcoma and Ewing's sarcoma.

In a first-in-human compassionate use study, [^{64}Cu]/Cu-NOTA-ch14.18/CHO PET/MRI successfully visualised GD2-positive neuroblastoma metastases and demonstrated potential for predicting and monitoring response to anti-GD2 immunotherapy [33]. A prospective cohort study of 11 paediatric patients subsequently confirmed non-invasive visualisation and quantification of GD2 expression across neuroblastoma, osteosarcoma, and Ewing's sarcoma [34]. Its principal value lies in enabling image-guided GD2-targeted immunotherapy and supporting theranostic development, with larger prospective trials needed [33, 34].

Advantages:

» GD2 is a tumour-associated antigen expressed in over 98% of neuroblastomas and minimally in normal tissues, conferring excellent tumour-to-background contrast

» Non-invasive whole-body quantification of GD2 expression across multiple paediatric tumour entities [34]

» Theranostic potential, as the same antibody construct can be paired with [^{177}Lu] for radioimmunotherapy [33]

Disadvantages:

» Clinical experience very limited; only compassionate use and small feasibility cohorts to date [33, 34]

» High background signal in blood pool and bone marrow at 24 hours post-injection may limit detectability of diffuse marrow infiltration [33]

» GD2 expression loss reported in up to 12% of neuroblastoma cases, generating false-negative results [33]

» Antibody pharmacokinetics require longer imaging protocols, potentially necessitating sedation in young children [33]

THE ROLE OF [^{89}Zr]/Zr-BEVACIZUMAB

Bevacizumab is a recombinant humanised monoclonal antibody-targeting vascular endothelial growth factor (VEGF), a key mediator of angiogenesis overexpressed in many paediatric solid tumours, particularly diffuse intrinsic pontine glioma (DIPG) and high-grade gliomas [38]. It has been used off-label in children for symptom control and radiation necrosis [35, 36]. While [^{89}Zr]/Zr-bevacizumab immuno-PET is not suited for routine paediatric imaging, it holds significant potential as a precision oncology tool in carefully selected children, particularly for predicting response to anti-VEGF therapy, characterising tumour

angiogenesis, and guiding treatment decisions in high-grade gliomas, DIPG, and neurofibromatosis type 2 (NF2)-associated schwannomas [35, 37]. Future paediatric-specific trials incorporating dosimetry optimisation are essential before broader clinical adoption. Figure 6 demonstrates [^{89}Zr]/Zr-bevacizumab in assessing DIPG [38].

Advantages:

» Targeted imaging companion to bevacizumab, revealing angiogenic heterogeneity invisible to conventional imaging

» Can inform go/no-go decisions for anti-VEGF therapy

Disadvantages:

» High radiation burden relative to ^{68}Ga - or ^{18}F -labelled tracers

» Long-lived ^{89}Zr required to match slow antibody kinetics; multi-day protocol logistically challenging for children

» Limited clinical data

THE ROLE OF [^{89}Zr]/Zr-TRASTUZUMAB

[^{89}Zr]/Zr-trastuzumab is a PET/CT radioimmunotracer for HER2-positive cancers, permitting whole-body mapping of HER2 expression and assessment of inter- and intra-tumoral heterogeneity. While clinical experience is well established in adult oncology, paediatric data remain limited to translational and early feasibility studies, with no prospective paediatric trials demonstrating clinical benefit. It shows promise as a biomarker to support HER2-directed therapy selection in osteosarcoma, paediatric gliomas, some medulloblastomas,

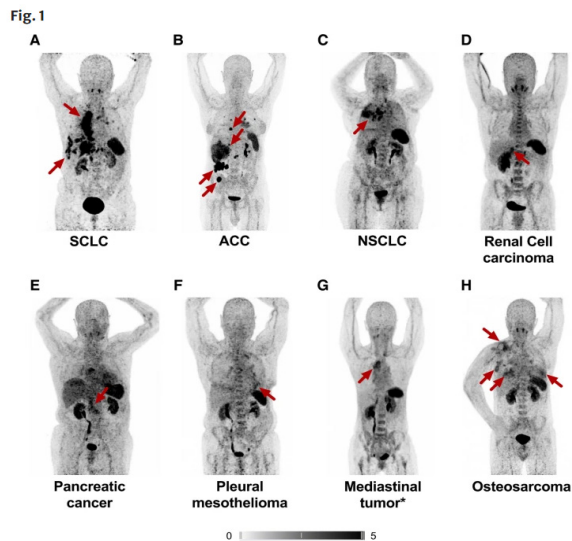


Figure 5. CXCR4-directed PET/CT using [^{68}Ga]/Ga-PentixaFor in different solid tumour entities. Maximum intensity projections (MIP) displayed. Red arrows highlight CXCR4-positive tumour lesions. ACC, adrenocortical carcinoma; NEN, neuroendocrine neoplasia; NSCLC, non-small cell lung carcinoma; SCLC, small cell lung carcinoma. Reproduced from Dreher et al. [31] with permission.

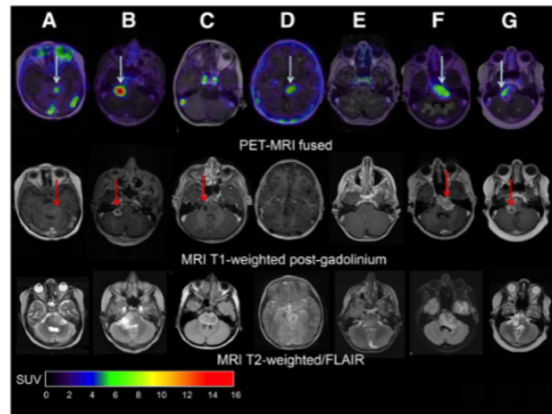


Figure 6. MR and PET/MR fusion images of patients with DIPG. (Top) [^{89}Zr]Zr-bevacizumab PET image (144 h after injection) fused with gadolinium-enhanced T1-weighted MRI. (Middle) Gadolinium-enhanced T1-weighted MR images. (Bottom) T2-weighted/FLAIR MR images. Five tumours exhibited variable [^{89}Zr]Zr-bevacizumab uptake (blue arrows); two tumours showed completely negative PET results. Positive PET results corresponded to contrast-enhanced areas on MRI [38]. Reproduced from Jansen et al. [38] with permission.

and potentially in adolescents with HER2-positive breast cancer [39–43].

Figure 7 demonstrates the biodistribution of [^{89}Zr]Zr-trastuzumab [44].

Advantages:

- » Strong adult evidence for use in tumour imaging and therapy selection

Disadvantages:

- » Very limited paediatric clinical data
- » High radiation burden relative to ^{68}Ga - or ^{18}F -labelled tracers
- » Multi-day imaging required over 3–5 days
- » Most paediatric tumours are not HER2-driven or express HER2 at low or variable levels

CONCLUSION

The development and clinical integration of novel radiopharmaceuticals for paediatric imaging are at a critical inflection point. Molecular imaging offers clear value in characterising disease biology, guiding

clinical decision-making, and monitoring treatment response; however, its translation into routine paediatric practice remains limited by radiation safety concerns, developmental pharmacokinetic variability, ethical constraints, and regulatory and economic barriers [45, 1]. Advances in dose optimisation, detector sensitivity, and standardised paediatric dosing have improved safety, while growing understanding of paediatric-specific disease mechanisms continues to shape biologically-targeted tracer development [46]. Emerging technologies including artificial intelligence-based reconstruction, ultra-high sensitivity PET detectors, long-axial field-of-view PET systems, and quantitative analysis further support dosage reduction without compromising diagnostic performance and reduce reliance on general anaesthesia in young children [47, 48]. Collectively, these advances have the potential to shift paediatric nuclear imaging toward precision-guided, child-centred molecular imaging that maximises clinical benefit while minimising risk [49].

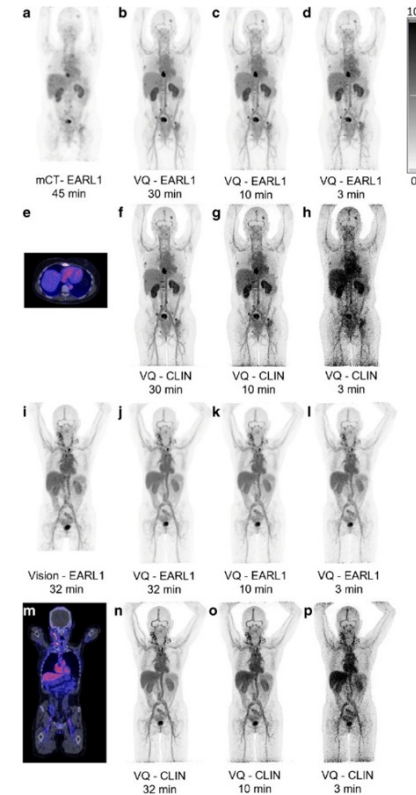


Figure 7. ^{89}Zr -Trastuzumab. Images acquired with Biograph™ mCT PET/CT (patient A) or Biograph Vision™ PET/CT (patient B). PET/CT images of patient A shown in top rows (a–h); patient B in bottom rows (i–p). Same intensity scale, SUV range 0–10, applies for all images except fused images (e, m) [44]. Reproduced from Brouwers et al. [44] with permission.

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