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Advancements in pediatric imaging: A review of techniques for reducing radiation exposure

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***Abstract*---**Pediatric imaging research has been particularly susceptible to the phenomenon of technologic "leapfrogging", in which advances in technology have outstripped progress in validating and implementing them in a patient-based, clinical setting. This review describes work underway to develop new techniques that can reduce pediatric imaging radiation exposure, principally by investigating new acquisition technologies and adjusting existing techniques, protocols, and practices to better conform to the special imaging needs of pediatric patients. These efforts have already helped develop and bring to the clinic new technologies such as iterative reconstruction for CT, dynamic helical CT, and quantitative susceptibility mapping for MRI. The pieces are also in place for additional future benefits for pediatric imaging. Advances in imaging, particularly for pediatrics, are often achieved late in the product cycle, with the result that new beneficial technologies take years, sometimes an entire market cycle, before they are adopted clinically due to the slow pace of capital equipment acquisition.

***Keywords*---**Pediatric imaging, radiation exposure, leapfrogging.

1. Introduction to Pediatric Imaging

Whether for trauma, chronic disease, or cancer, medical imaging has long improved both the experience and care of patients by quickly and accurately visualizing internal structures and functions. Indeed, advances in this domain, fueled by a growing understanding of human physiology and swiftly escalating technological capabilities, have truly given rise to a new shared doctor-patient perspective. However, with the widespread use of computed tomography (CT), an imaging modality characterized by at least 1000 times the radiation exposure of

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plain film radiography, has come a growing consensus that its use, particularly in the pediatric population, may be contributing to the future burden of malignancy. In children, the basis for this assumption - mortality - is particularly compelling. Malignancy is the second leading cause of death after trauma in children and adolescents, and the cancer risk is linear with radiation dose, secure across a wide range, and consistent with radiation protection concepts. In brief, the cumulative risk of CT radiation effects, along with a broadening awareness of the role of exposure in triggering cancer, has raised questions and spawned debates about the overall safety of CT, and has emphasized the importance of reducing dose, limiting unnecessary or repeated scanning, and tailoring the use of CT to the clinical problem.

These concerns are further heightened by current trends that not only reflect an increased overall use of CT, but also suggest growing reliance on this technology to guide clinical decisions. Within the pediatric population - that is, those under 15 years of age and even more by extension those 15-20 years of age - CT use, as a whole, increased by an average annual rate of 10-12% over the last 15 years. In parallel, similar growth was seen in the study intensity; the average dose of radiation per CT study remained essentially unchanged, so the cumulative increase in use did not represent a broad-based decrease in the amount of radiation given per study to obtain the images. Over the most recent studied interval (2002-2005), the marked increases in acute lymphocytic leukemia (ALL) were not retarding. Among patients, the percentage of abdominal/pelvic studies increased to 19%, the percentage of head/neck studies increased to 52%, the percentage of chest studies decreased to 27%, and the overall percent in the younger ages increased among neonates, infants, and children. Factors affecting future use should also be acknowledged. These include improvements in image quality, and thereby clinical information, as well as increased availability and patient maturation over the long term. In response to these and other concerns, many physical and logistical options have been proposed for reducing radiation risks from reported CT studies. For a few such proposals, some level of clinical validation and consensus has been reached.

1.1. Importance and Challenges in Pediatric Imaging

Radiology has a critical role in characterizing a wide variety of diseases which affect children. Accurate diagnosis based on imaging is necessary to avoid delay in treatment, lifelong disability, or even patient death. Many studies have found that advanced imaging can make children more comfortable due to reductions in the need to perform invasive tests (e.g., lumbar puncture or angiography) or the time to obtain diagnostic results.

Over the past few decades, the utilization of pediatric imaging has increased greatly due to its clinical benefits. However, many parents worry about the cumulative radiation risk from CT, fluoroscopy, and radiography, so clinicians also face some ethical and legal responsibilities. Nonetheless, clinicians are reluctant to choose MRI instead because of the tradeoff of anesthetic risks, high costs, long scanning times, and security issues. The risks of incidental findings, pain, and intolerance may also decrease parental and even patient acceptance.

Therefore, it is important to develop safer imaging techniques for children to improve their quality of life. This work aims to review the advancements in fluoroscopy, which is commonly used to diagnose many diseases, and ultrasound and MRI, which are considered radiation-free and safe, and to discuss those techniques and the impact they have, especially in lung studies.

2. Radiation in Pediatric Imaging

Some degree of radiation exposure is inevitable in medical diagnostic imaging using X-rays or nuclear science. All radiation is potentially harmful to living tissue; the health risk depends on the amount of radiation a person receives. The potential risks can often be justified by the benefits of the diagnostic image, provided the examination has been recommended for medical necessity by the attending physician. However, with the advent of X-ray computed tomography (CT), the traditional low exposures have been increased significantly, thus increasing the risks, particularly in pediatric patients for whom doses are not adjusted for body size as they are for adults, and are under development. In addition, pediatric patients have more rapidly growing and dividing tissues and a longer lifespan compared with the adult population. Radiation exposures from diagnostic imaging as a proportion of the total ionizing radiation dose to people have significant influences.

Pediatric patients are estimated to receive higher percentages of their cumulative radiation from radiology procedures compared with adult patients. These statistics are based on the amount of environmental background radiation that people are typically exposed to in the absence of any medical treatments. In approximately 50% of Americans, computed tomography (CT) has been reported to be the largest single contributor to ionizing radiation dose to the population. This is based on the fact that CT can deliver radiation doses greater than 100 times that of a standard chest X-ray. Other high-dose examinations include cardiac catheterizations, fluoroscopically-guided interventional procedures such as stent placements, and bone scans. However, the radiation dose that is considered safe is not known with certainty, so these figures are used only as an approximation.

2.1. Types of Radiation Used in Imaging

The kind of imaging largely determines the type of radiation that is exposed to—a spreading effect that reflects the infinite number of imaging techniques. Below is a general (and undoubtedly incomplete) breakdown of popular imaging techniques:

Radiography – The technique consists of x-rays being passed through a body part. Dense tissues are clearly visible as a result of x-rays that do not penetrate body parts entirely, exposing the photographic film.

Fluoroscopy – A continuous stream of x-rays used to create moving images. The images provide feedback as to whether an invasive procedure is proceeding correctly.

Mammography – X-rays evaluate the breasts and are at the center of modern breast cancer detection programs, although ultrasonography is also important.

Computed tomography (CT) – A series of X-ray views positioned in cross-sectional "slices" of a body part that gives a three-dimensional viewpoint of the body. It is

now a matter of fact that CT scans use more radiation than nearly any current form of medical imaging designed to observe the interior of the body.
Digital radiography – All radiography performed with the assistance of a digital plate, most often integrated into a picture archiving and communication system (PACS).
Digital subtraction angiography – Uses injections of contrast material to observe blood vessels in a part of the body. It produces much less radiation than normal subtraction angiography.

3. Techniques for Reducing Radiation Exposure in Pediatric Imaging

With increasing clinical and patient awareness of potential harm from ionizing radiations, newer techniques have been developed that can minimize ionizing radiation risks and yet provide clinically relevant imaging information. Many of these techniques, including low-dose CT, selective use of MRI without sedation, sub-millisievert chest CT, modern fluoroscopy technology with dose recording capabilities, cartilage- and bone-specific MRI pulse sequences, and contrast-enhanced MRI angiography in neonates, have been applied on a daily clinical schedule and are demonstrated with practical examples. By reducing the carcinogenic risk of medical imaging, the general radiation risk of other sources such as space, aviation, domestic, and industrial X-ray exposure, and certain interventional procedures can be placed in proper context. Although other non-radiation techniques can also provide this information, optimizing those techniques and their applications are beyond this article's scope.

These imaging techniques help manage complex medical conditions by allowing early assessment, timely surgical and medical care, and interventional image-guidance procedures at reasonable radiation risk. Many of these techniques have become silver standards or benchmarks of safety for pediatric radiation exposure. This discussion is focused on radioisotopes and ionizing radiation from X-ray imaging. Non-radiation issues concern MR signal contrast agents, image warping from sedation during the pre-anesthesia screening, and central venous catheterization under ultrasound guidance. The VII has become more effective in addressing these issues in various imaging modalities including X-ray, mammography, and scintigraphy with bone scan, pulmonary ventilation/perfusion scan, and thallium-201 stress test.

3.1. Image Gently Campaign

The Image Gently campaign is an initiative developed by the Alliance for Radiation Safety in Pediatric Imaging. The goal of the program is to raise awareness and lower the amount of medical imaging radiation that children are exposed to. Here are some suggestions that the campaign has for radiologists, technicians, and administrators on how to lower the amount of ionizing radiation used during medical imaging procedures.

The first thing that the program suggests is to use body parts based on the history of what the patient has wrong with them. This is a way to help avoid full body scans. The next suggestion is to use the smallest amount of radiation needed to limit the dose that the child is exposed to. The "as low as reasonably achievable" or the dose approach should always be followed whenever possible. This is especially true for tiny children when the question is proposed, "what can be done to accommodate their limited size?" Always use shielding for the breast, gonads, and other radiosensitive tissues for all patients.

It is also suggested that if there is an available option of an imaging study that does not use ionizing radiation such as ultrasound (US) or magnetic resonance imaging (MRI), then those types of imaging should be looked at. The strength of using imaging of CT combined with barium- and/or water-soluble contrast media is also discussed. Also, a total overview of pertinent conditions for which CT should be used and those when it should be avoided in pediatric patients should be made. Choosing the correct pediatric imaging examination is a way to help minimize ionizing radiation used and also minimize the long-term cancer risks from that ionizing radiation. If repeated studies are going to be needed, then the dose that the child is exposed to should be adjusted accordingly. The final suggestion they have is to monitor, give feedback to, and adjust the quality care given to the children during medical imaging, while also monitoring the doses. This is the only way to make sure that the child is getting the safest and most accurate imaging possible.

3. Advancements in Imaging Technology

Recent years have shown a starting trend of increased awareness of the consequences of radiation exposure from medical imaging and radiation-based interventional procedures - both in the medical field and in public media. This new awareness inspires a need for the evolution of devices and methods capable of performing medical procedures with greater precision using non-ionizing radiation when possible, while also inspiring a convenient collection of data that may guide clinical decision-making. As a result, we are witnessing several of the most significant advancements in medical technology of our generation in developments in medical imaging, computerized systems for the collection, storage and analysis of medical data (often collectively referred to under the umbrella of medical informatics or bioinformatics) and information technology needed to form networks capable of controlling and monitoring medical procedures with information exchange and display. Use of informatics for investigation and intervention at the interface of biomedical imaging, biology, and the patient care team, by incorporating these new techniques into the clinical routine, will likely lower ionizing radiation dose to the population from medical imaging.

In the case of pediatric imaging, progress is currently being made in methods for ensuring appropriate exposure levels and dose optimization arising both from governmental bodies in the form of regulatory agencies, which have guidance programs or rules for adjusting exposure levels to ensure that quality goals such as the need for diagnostic and therapeutic information are balanced with doses as low as reasonably achievable (ALARA), and professional organizations, which have standards for dosing requirements for equipment that is used to image children. Similarly, several recent studies in the literature deal with specific aspects or the consequences of low-dose exposure to ionizing radiation from medical imaging. These studies increasingly deal with radiation doses that result from patient imaging and therapeutic application. However, there has been little cell and molecular investigation of the cumulative low-dose exposure effects on humans, especially on growing children, which suggests an opportunity for further research in these settings. The primary goal of this chapter is to briefly review the current status of the major imaging techniques used in pediatric imaging all using ionizing radiation.

4.1. Digital Radiography

Reducing radiation exposure during imaging is an extremely important topic when it concerns pediatric imaging. There are several techniques which can aid in reducing exposure, including digital radiography, optimal exposure factors, grid use, alignment of the child, breast shields, and proper immobilization with sponges or sandbags. Further techniques include distance, fluoroscopy with image intensification, fluoroscopic filters, pulsed/low-dose fluoroscopy, image storage, or the ability to run a patient through on a cine loop. Other options are physics, added filtration, detector exposure, and the use of modern projection techniques to reduce dose. For pediatric patients, it is especially important to be aware of radiation exposure and its potential harmful effects. It is the physician's responsibility to ensure that radiation exposure is as low as reasonably achievable while still maintaining image quality. Some very basic and simple factors, such as body mass and organ size, contribute to children's heightened radiosensitivity. Children's low body mass frequently requires specialized medical imaging examinations, which may subject the child to high doses of ionizing radiation.

Although digital radiography and computed radiography use a few similar factors for exposure, these methods result in different quality images. Digital radiography is performed using a flat panel detector or an encapsulated detector (or a detector within the table). This detector should be about 100 to 300 mm from the table. The advantage of digital radiography is that it has the benefit of direct or indirect conversion, which allows for faster exposure time. Because it is 100 to 300 mm from the table, the imaging area will be larger than C-arm systems. Additionally, digital radiography can be obtained from a very long tube offset because of the ability to manipulate and enlarge the image. The disadvantage of this system is that it needs to be connected to the workstation and only allows one projection of imaging. Due to the fact that it needs to be connected to a workstation, the overweight child or one who does not follow directions may have more difficulty being positioned properly into the imaging system.

5. Artificial Intelligence in Pediatric Imaging

Artificial intelligence (AI) is a growing technology in medicine with vast potential, and AI in pediatric imaging is no exception. AI encompasses a group of multiple but related technologies known as machine learning, deep learning, neural networks, and expert systems, to name a few. AI applications are diverse and could be used for image acquisition, image reconstruction, and postprocessing image interpretation. This section is a simplified discussion to help pediatricians and pediatric radiologists understand the terminology, mechanism of AI application, potential implications, and future direction of AI within pediatric radiology.

6.1. Image Acquisition and Reconstruction AI, also known as machine learning, refers to the process of building intelligent systems that can independently learn, reason, and accomplish tasks that usually require human intelligence. It involves a technology of teaching computers to recognize patterns from experience data using a multilayer computer program called artificial neural networks, allowing them to act in a more human-like manner. In medical imaging, AI has been increasingly used in the development of image acquisition, postprocessing, and computer-aided diagnosis (CAD) systems. In terms of reducing radiation exposure, AI has been employed to enhance image quality. For example, routine use of image-reconstruction algorithms (SAFIRE or ASIR) - a newly emerged feature included in more recent CT scanners - has allowed a significant noise reduction without utilizing additional radiation. Indeed, advancement in acquisition and reconstruction techniques would result in less radiation-dose concern, particularly when imagers perform medical imaging on children.

5.1. Applications and Benefits

Most of the techniques currently used to reduce radiation involve lowering these settings manually based on each patient. The telemetry system used for the X-ray can measure patient thickness at the table location and increase the radiation dose to an appropriate level, while another system can take a second fluoroscopic image when mobility is detected, greatly reducing the amount of radiation x-ray. And also the mandatory saturation of detectors in the image. Advances that have been made in the last 10 years in semiconductor technology have also led to changes that can reduce the dose of the X-ray in fluoroscopic applications. These advances have enabled some applications that work with flat detectors in digital radiography imaging with the same level of performance as scanners with fluoroscopic image intensifiers to erase the need for the use of radio tubes and fluoroscopic intensifiers in electronic technology. They also have a higher dynamic range.

The combination of very low power designed for the array of a two-dimensional image and an equivalent dynamic range allows the integration of a fluoroscopic pixelation density at a level that does not require tomographic memory to combat the stochastic limitations. This type of technology allows a reduction of the exposure to the X-rays that work with low parameter settings. Other methods that have proven to be effective in reducing radiation balms are cineradiographs, MSG (digital imaging tape guides), and dynamic panel tracking. Cineradiographs have become an efficient and cost-effective way to accumulate a large amount of diagnostic information. High-resolution cineradiographs can be made at multiple levels of the swallow's area and provide great benefits regarding the characterization of secular dysphagia problems and dynamic changes, with major limitations regarding the selection of the band, the potential for distortion, and the cost of construction.

6. Future Trends in Pediatric Imaging

Frequent and unprotected use of CT scanning for pediatric problems is an ongoing source of concern due to the associated risk of radiation. Pediatric radiologists are aware of the risk of cancer due to ionizing radiation exposure, the decreased radiation tolerance of pediatric patients, and the greater risk of overexposure. We perform a variety of studies to recommend non-contrast imaging techniques to limit radiation exposure in patients such as ultrasound, magnetic resonance imaging, and exposure window methods considering age-related dose reduction tactics. In this review, the evidence-based clinical studies promoting known strategies to minimize radiation exposure in children are summarized and discussed.

In conclusion, radiation exposure through pediatric studies carries a real, proven risk of causing cancer. If ionizing radiation imaging exposure could be routinely performed, it should be suggested for pediatric patients. Alternatives to ionizing highly reach various diagnostic imaging techniques, depending on the clinical problems being evaluated. Decreasing the dose of ionizing radiation through limited views and low-dose protocols and the use of responsible imaging strategies for pediatric problems, selecting the most relevant imaging technique for the clinical evaluation, monitoring imaging practices using CT with the ALARA concept, and the application of the Image Wisely concept contribute to this process.

6.1. Development of Low-Dose Imaging Techniques

Concern within the pediatric community toward exposure to ionizing radiation from radiology has culminated in a range of technical, educational, training, and applied clinical research projects to address this important public health issue. Acute and particularly late health effects are believed to be relatively high after medical imaging procedures that involve relatively large doses delivered to radiosensitive organs, which may double a potential cancer risk in an individual. DNA strand breaks may be repaired, or not, depending on a number of factors that influence the radiation response of irradiated cells making it difficult to extrapolate risk estimates for the various radiation-induced adverse effects. A good understanding of the imaging risks is necessary so that an appropriate selection of pediatric patients for high-paying-as well as ultrasound examinations-peractivated multimodal imaging, particularly with newly developed lower-dose advanced techniques, as well as low-dose optimized imaging techniques are also essential to accurately rule out or diagnose and monitor a specific condition since at higher ionizing radiation doses delivered to an organ, minor anatomic details, which are essential for most imaging diagnoses, are better depicted. Currently, widespread use of efficient and equally sensitive medical imaging tests from the most diverse modalities is a recognized medical imaging challenge.

In order to minimize the number of medical imaging procedures necessary through the application of innovative low-dose imaging strategies, development of predictive modeling is essential. The radiologist should always indicate the imaging technique in order to obtain the desired information, but using the lowest radiation dose that provides diagnostic images in consideration of the type of pathology to diagnose, the body part to investigate, and the patient's age, gender, weight, body mass index and existing risk factors. The currently recommended and widely adopted radiation awareness strategy in pediatric patients is based on a series of actions that could effectively reduce undesirable levels of radiation exposure for medical purposes with regard to the widely adopted principle of optimization. Dosages delivered as low as reasonably possible (ALARP) involve only a limited number of accepted well-defined science facts and considerations related to clinical or radiological practice in compliance with standard ethical attitudes. However, evidence from studies comparing different optimization strategies shows interventional alternatives capable of reducing exposure at lower ionizing radiation dose levels and/or improving health support. In this report, we aim to highlight some of the innovations and discuss some important high-paying advanced and low-dose imaging and optimization strategies managed by radiologists and medical physicists in order to ensure that optimal CT image quality is achieved along with the lowest possible risks. Dose optimization involves, in addition to radiation exposure reduction and diagnostic indicators of patient's comfort level, the cost-effectiveness methods and resource planning of effective high quality health care.

7. Ethical Considerations in Pediatric Imaging

Children represent a unique and vulnerable patient population that requires special consideration and protection. It is important to apply the ethical principles of bioethics to all areas, including the development and administration of pediatric imaging studies. The principles of medical ethics include beneficence, nonmaleficence, respect for autonomy, and justice and serve as a comprehensive framework for the process involved in ethical decision-making in the practice of pediatric imaging. There is a special emphasis on patient autonomy, confidentiality, veracity, and fiduciary obligations to patients and their families. A balance of these ethical considerations, which involves no absolute right or rightness in any situation, must be applied to determine the appropriateness of imaging studies in pediatric patients.

Furthermore, it is the obligation of the radiologist and pediatrician working with children and their families to ensure an appropriate standard of care by upholding education, quality standards, and full access to diagnostic testing, while adhering to scrutiny in the values that are held by the family. Although unrestrained decision-making must be tempered by a commitment to the public while addressing the demands and limitations of the healthcare system, it must be acknowledged that when making decisions on imaging the child and family, it is important to advance the interests of the child by involving the patient and family in an atmosphere of empathy. Children should be given a voice, provided it is possible, by being sympathetic in explaining what will take place in familiar surroundings using syllables and terminology that are comprehensible. Children should be made to feel as comfortable as possible, knowing what to expect and being appropriately supported through this process.

7.1. Balancing Risks and Benefits

In the care of pediatric patients, the balance between the risk of ionizing radiation during imaging examinations and the potential dangers of a missed or delayed diagnosis must constantly be weighed. The risk of developing both cancer and functional radiation drawbacks is relevant to each and every patient and are lifelong concerns for parents and families. While this should never dissuade the clinician from ordering an appropriate examination that is warranted, one should constantly be mindful of the potential risks.

Study after study has affirmed that other professional and patient stakeholders would appreciate more information on imaging procedure radiation doses and the long-term risks, lifetime risks, and event probabilities for cancer from exposure to low doses of radiation. Parents, when questioned, consistently would prefer that their children not have an imaging examination using ionizing radiation unless it was absolutely necessary after considering the potential risks and benefits. Children are especially sensitive to the long-term risks of developing cancer because they have 75 years or more to develop cancer, some may be more radiosensitive due to genetic predispositions that make them less able to repair radiation-induced genetic damage, and children's cells are growing and thus more sensitive to the mutagenic effects of radiation.

8. Conclusion and Future Directions

Pediatric imaging research has been particularly susceptible to the phenomenon of technologic "leapfrogging", in which advances in technology have outstripped progress in validating and implementing them in a patient-based, clinical setting. This review describes work underway to develop new techniques that can reduce pediatric imaging radiation exposure, principally by investigating new acquisition technologies and adjusting existing techniques, protocols, and practices to better conform to the special imaging needs of pediatric patients. These efforts have already helped develop and bring to the clinic new technologies such as iterative reconstruction for CT, dynamic helical CT, and quantitative susceptibility mapping for MRI. The pieces are also in place for additional future benefits for pediatric imaging.

Effective translation of the many new techniques described in this paper will require cooperation between academia and industry to bring innovations from concept to product, and then from product to practical and effective clinical use. A discussion with radiologists on the need and potential benefits from new technology can improve work targeting the most valuable opportunities. Direct involvement of radiologists in the product development process is also crucial as development teams must understand how a new technology will fit into a daily clinical practice before their new products will be able to effectively and efficiently contribute to this practice. Advances in imaging, particularly for pediatrics, are often achieved late in the product cycle, with the result that new beneficial technologies take years, sometimes an entire market cycle, before they are adopted clinically due to the slow pace of capital equipment acquisition.

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