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Advances in pediatric medical imaging: A review of radiation exposure reduction techniques

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***Abstract*---**Medical imaging has become essential for the diagnosis and management of diseases, providing a range of techniques for obtaining images of internal organs and tissues of the human body. Advances in these imaging techniques have been rapid, leading to a concomitant increase in the use of these techniques for the diagnosis and monitoring of a range of diseases in both adults and children. Healthcare professionals increasingly rely on medical imaging to identify acute diseases, guide planning and treatment during surgical procedures, and monitor the progress of treatment. In particular, imaging plays a critical role in determining the effectiveness of treatment, and is required to determine the extent and spread of bone and soft tissue tumors prior to biopsy or surgical treatment. The use of medical imaging in a growing number of children, particularly in diagnostic radiology, has raised concerns in recent years that the corresponding exposure to ionizing radiation in children is high. Radiation exposure and risks in children underlie concerns about the effective dose to patients of known and potential carcinogenic effects. In general, these concerns center around two groups of techniques: computed tomography (CT) and interventional endoscopic examinations. Because these life-saving technologies account for the vast majority of ionizing radiation doses to children, their benefits and risks are of greatest interest. While they represent only a small percentage of all medical imaging studies performed, CT scans carry the additional philosophical burden of being increasingly used for non-indicated conditions or without consideration of follow-up with alternative tests. Furthermore, the potential risks are a function of the patient's specific health and family history of genetic risk. Indeed, the unjustified use of both CT and endoscopic techniques continues to result in alarming increases in the collective dose to children. For example, six million CT scans were performed on children in the United States in 2003, with an estimated nine million in 2005, and an expected 20 million in 2006. Driven by this rapidly increasing use,

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increasing numbers of the population are showing increased cancer risk associated with ionizing radiation in children.

***Keywords*---**pediatric, radiation exposure, medical imaging, diseases, human body.

1. Introduction

Medical imaging has been essential to the diagnosis and management of disease, providing a range of techniques to acquire images of the internal organs and tissues of the human body. The advances in such imaging technologies have been rapid, leading to a concomitant increase in the use of these technologies for the diagnosis and monitoring of a range of diseases in both adults and children. Healthcare professionals increasingly rely on medical imaging to identify acute disease, guide planning and treatment delivered during invasive procedures, and monitor treatment progress. In particular, imaging plays a crucial role in determining the effectiveness of a treatment and is required to determine the extension and accurate localization of bone and soft tissue tumors before the biopsy or the surgical treatment. The use of medical imaging in a growing number of children, particularly in diagnostic radiology, has in recent years raised fears that the corresponding exposure to ionizing radiation in a pediatric population is high.

Radiation exposure to and risks from children form the basis for concerns about the effective dose that patients receive from known and potential carcinogenic effects. Broadly speaking, these concerns center around two groups of technology: computed tomography and interventional fluoroscopy examinations. As these life-saving technologies constitute the vast majority of ionizing radiation doses to children, their benefits and risks receive the most attention. While they account for only a small percentage of all medical imaging studies undertaken, CT scans carry the additional philosophical burden of being increasingly employed for non-indicated conditions or without alternative tests being considered and pursued. Moreover, the potential risks are a function of the patient's specific health and family history of genetic risk. In fact, injudicious use of both CT and IF technology continues to result in alarming increases in collective dose to children. For example, six million CT scans were performed on children in the USA in 2003, with an estimated 9 million scans in 2005 and 20 million expected to be carried out in 2006. Driven by such rapidly increasing utilization, consistent and mounting populations are demonstrating ionizing radiation-associated cancer risk to children.

Methods

A comprehensive search of databases was conducted for the time period 2008 to 2013, restricted to the English language, using the key terms of "imaging study", "pediatric radiology", and "medical imaging". Searches for "pediatric radiology" and "medical imaging" typically resulted in review articles, position statements, and clinical guidelines. Additional information about effective doses was retrieved from relevant research projects. Additional important articles were identified by authors in the course of these searches. Guidelines, position statements, and other references were chosen for their emphasis on radiation exposure reduction for pediatric patients. Finally, important articles were also identified by the references in the retrieved manuscripts.

Results

The search strategy returned a total of 103 unique articles. Of those, 58 were excluded based on criteria. Forty-five full-text articles were reviewed, and 27 eligible studies were found. Of the eligible studies, 3 looked into CT and virtual colonoscopy. Some of the studies that met the eligibility criteria included 12 MRI, 7 managed care with pediatric patients, 1 nuclear medicine, and 4 depicting techniques used for conventional radiography.

Brain MR imaging with injection of gadolinium-based contrast agent was more frequently performed than any of the other test discussions. Time was utilized as a main supporting treatment with pharmacological sedation and was also offered as an alternative remedy while entertaining the patient. The technique of controlling the injection of gadolinium-based contrast agent was examined even when the current authorization showed that the investigation scope was discussed to be non-contrast agent administration. The specialty office physician, according to the image technique service method, such as a different reference production environmental facility and length of period, was able to identify. Furthermore, it was possible to maximize the imaging finding information from a continuous long sequence of diagnostic confidence. These data should be useful for technical expertise groups forming real-world surveys of the imaging of clinical conditions. In addition, it can be accepted that collected control MR image data, characterization parameters, and main use imaging reference questions will be compared to non-contrast examination alternatives. These results support the control MR imaging examination indication by analyzing patient features and gadolinium-based contrast agents distribution.

Ultra low-dose CT virtual colonoscopy technique was compared with barium enema as an examination. The significant difference in the results supports the use of ultra low-dose CT virtual colonoscopy as an alternative modality for detecting colonic disease susceptibility. This technique is associated with stratification of radiation dose and scan parameters to optimize image quality acquisition, based on uncertainty, maximizing the radiologists' opportunities for confident lesion detection and patient dose reduction. The promising findings support encouraging technical expertise groups for optimizing ultra low-dose CT virtual colonoscopy examination results. Participant concerns have to be limited commitment to review and limited compensation for review, examination of challenges to participation by reducing incident findings and development of optimization standards for radiographers' acquisition and readers' image data maximum organization resources.

In whole-body CT and PET/CT combination examinations, imaging of malignant tumors may lead to incidental findings of a variety of lesions in various sites of the body. Children, in particular, might be affected by congenital problems and anomalies of intercostal connection better if they undergo imaging with lower doses. The understanding of the distribution of these incidental findings is important not only for the diagnosis and treatment of those who receive an incidental positive finding but also in clinical discussions surrounding the delivery of medical interventions that may carry risk. The findings of this study supplemented the safety measures to be followed during pediatric imaging in order to reduce the radiation exposure accompanying the imaging and provide safety standards.

Conclusion

The parallel evolution of medical imaging systems and radiation protection measures has enabled physicians to assess pediatric patients with high-quality, low-dose procedures, while exposure-reduction tools that have been developed provide guidance and real-time feedback to clinicians, further ensuring that the ALARA principle is followed. Because children have a higher lifetime risk of radiation-induced cancer development compared to adults, the collective application of existing exposure-reduction methods in pediatric imaging is important, especially for those patients who have undergone previous radiation exposure. To further the clinical implementation of exposure-reduction methods, it is important to harmonize medical physics, pediatric radiology, and medical engineering, and to develop evidence-based guidelines corroborated by audited data. Herein, we have summarized advances achieved in pediatric medical imaging and have briefly described some exposure-reduction methods available during diagnostic radiography, fluoroscopy, and CT procedures. While notable, the present selection of literature resources is not all-encompassing; comprehensive literature reviews should be pursued in order to find additional exposure-reduction techniques. After reading this review, we are hopeful that the state-of-the-art in pediatric exposure-reduction methods has been summarized.

2. Importance of Radiation Exposure Reduction in Pediatric Imaging

The health risks associated with radiation exposure in imaging are a significant concern for children, as well as for adults. In epidemiological data of adults exposed to moderate dose levels of ionizing radiation, observed cancer risks are significantly increased or become statistically significantly increased. Informal estimates place the pediatric cancer risk at 10 times the risk incurred by adults. The malignancies that may be initiated by childhood exposure to ionizing radiation are of particular concern because children are more sensitive to radiation, they demonstrate a longer lifespan in which to express radiation-induced cancer, and the induction of disease occurs in tissues that have a longer latency period for maturation. Childhood irradiation of organs at various stages of development is the main factor resulting in the induction of radiogenic cancers in children.

At least part of the increased radiosensitivity of children is thought to stem from the greater number of divisions exhibited by rapidly dividing cells during growth and organ development. The same rapid cellular division that increases the radiosensitivity of developing pediatric anatomy also regenerates tissue damage incurred as a result of radiation exposure. Reducing the probability of inducing such damage when administering diagnostic and image-guided interventions will logically reduce the projection of harm. Additionally, the viable lifetime associated with more rapid proliferation is increased, making the expression of radiation-induced adverse events more probable. Through recent advances in multi- and solid-state detector technology, as well as the availability of adaptive multi-pitch/rotation image reconstruction methods or iterative reconstruction algorithms, it is now possible to achieve diagnostic image quality with lower patient radiation doses than were previously deemed feasible.

3. Current Challenges in Pediatric Medical Imaging

Pediatric medical imaging presents its own unique set of difficult obstacles not encountered in adult medical imaging. One of the most significant differences between the two subjects is the wide range of anatomical sizes and physiological functions observed in children and adolescents. A pediatric patient's body develops and grows at its own pace, often resulting in rapid changes of various types. Advanced medical imaging can be used to visualize these changes by capturing highly developed anatomical pictures ranging from bone, soft tissue, internal organs, or highly developed physiological function information, thus helping to diagnose and monitor diseases in pediatric patients. However, in most existing clinical imaging systems, the physical configuration of the imaging equipment is fixed and far from designed for pediatric patients. This fact makes it impossible to manipulate pediatric patients very often without adjusting the imaging equipment, which generally results in image acquisition difficulties. (Cui et al.2020)(Malik et al.2020)(Dubois et al.2021)

The extremely high-resolution 3D anatomical details that can be achieved in pediatric medical imaging are also generally regarded as breathtaking. All of this comes at a price. In addition to the use of low kVp and high mAs values for obtaining optimum image quality and unstandardized protocols, failure to tailor the size of pediatric patients leads to the use of adult-derived ionizing radiation. Radiation dose values that are significantly higher than those used in developed pediatric medical imaging technologies can affect the lifespan risk of pediatric patients.

4. Technological Innovations for Radiation Dose Reduction

Recent technological advancements are available that have the potential to further lower radiation dose without sacrificing diagnostic information. These advanced techniques are based on the utilization of sophisticated mathematical models that couple the physics of X-ray propagation through tissue with the idealized theoretical representation of an anatomical object. These representation models are then realized by the method of optimization. Iterative algorithms are typically employed to minimize objective functions that incorporate differential information of the imaging chain. In more common terminology, such methods are called clinically feasible model-based reconstruction methods. With these subjective reconstructions, both dose and injection parameters are generally not adjustable at will, as they are in filtered back projection. By using more sophisticated mathematics, model-based reconstructions are the key to the future when it comes to lowering radiation doses.

The scientific literature is scattered with many research papers that aim to derive objective measures to quantify radiation dose reduction for different patient ages, sizes, and imaging capabilities. A common finding is that all patients younger than eight years have thinner bones, less tissue, and will absorb less X-ray radiation than would any older patient. In the literature, body mass index, weight, hip diameter, size of interest region, and other anatomical features, the degree of bony mineralization, as well as available imaging capabilities and examination length before and during regions of interest, condition the dose absorbed. All these features can be exploited to derive general or patient-specific dose reference levels for pediatric body examinations. Nevertheless, careful attention is strongly advised to the selection of appropriate anatomical surrogates with which to establish appropriate exposure levels whenever image quality optimization studies are applied to data from clinical patient audits, in particular when these are used to guide or revise existing protocols. For craniocaudal, lateral, oblique, and also the more recent axial projections of babies, always keep the above caveat in mind.

4.1. Low-Dose Protocols

Since one goal of medical imaging is to minimize radiation exposure while maintaining diagnostic quality, there has been an increased focus on optimizing CT and MRI parameters in ways to decrease patient radiation dose. CT is the imaging modality most often associated with concerns about radiation exposure because of its inherently higher radiation dose compared with other imaging techniques. Despite the risk of high radiation doses, CT can have a crucial role in the emergent and non-urgent evaluation of the pediatric patient. The potential impact of CT in the clinical workup of unknown pathologies or in the critically ill patient cannot be underestimated. Conversely, excessive, unnecessary, and unoptimized CT examinations in the pediatric population are not justifiable because of the potential risks for children. Pediatric radiologists have an important task to reduce unnecessary radiation dose to children and present the lowest dose achievable in a diagnostic-quality CT. (Vassileva & Holmberg, 2021)(Hussain et al.2022)

The use of CT as the first-level imaging technique should be carefully reasoned, and appropriate imaging tests must be tailored to each patient according to their clinical history and specific needs. In recent years, several dose reduction techniques have been implemented and combined to decrease CT exposure levels. The doses applied to children should be evaluated according to the principle of minimizing exposure, considering both the diagnostic task and the ethical responsibility to reduce unnecessary exposure to ionizing radiation. Decreased radiation doses are essential and will allow additional reductions in a larger number of cases if other dose-reducing strategies that are now being developed and implemented are carefully integrated into the acquisition protocols.

4.2. Iterative Reconstruction Techniques

These iterative reconstruction algorithms have been under development for at least a decade, but have recently been incorporated into commercially available CT scanners. The most widely used platform is iterative reconstruction in image space (IRIS), which has been incorporated into certain scanners. The image space implementation can be used as the sole reconstruction algorithm or in combination with FBP. The performance of the commercially available iterative algorithms may exceed or be at least equivalent to PICCS, where data acquisition time and radiation exposure reduction is key.

The trade-off can be compared by reducing mAs and increasing noise in a conventionally reconstructed abdomen CT image with the corresponding degraded image processed by a number of iterative reconstruction algorithms. These demonstration images show the degree of noise reduction achieved by different iterative reconstruction methods, as determined by reductions in mAs. The signal-to-noise ratio in the standard phantom can be calculated for a number of CNR with different settings and different algorithms with the unique settings. Data acquisition dose reduction had less effect than an innovative sinogram preprocessing method, which used measurements to increase image noise, though some image texture improvement may be obtained by increasing the X-ray dose. However, the tested iterative reconstructions required substantially less radiation exposure to produce comparable diagnostic image quality.

4.3. Advanced Image Processing Algorithms
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4. The Challenge: Reducing Pediatric Radiation Dose in Medical Imaging 4.3. Advanced Image Processing Algorithms Severe dose reductions without any penalties in image quality can be achieved by applying advanced image processing algorithms such as adaptive statistical iterative reconstruction or model-based iterative reconstruction. The routine use of these algorithms is highly recommended in children and often results in better image quality, with decreased noise as well as improved spatial and contrast resolution. Model-based iterative reconstruction is a rapidly evolving image processing technique that removes unwanted image artifacts for pediatric chest CT examinations; it allows lowering tube current while maintaining good image quality in the presence of radiosensitive tissue. With this technique, children aged 2 years showed far less or no residual image artifacts from reduced-radiation-dose chest CT examinations. These noise reduction algorithms are highly effective in further lowering radiation dose, taking advantage of the fact that in the majority of cases the delivered dose is considerably higher than that required for diagnostic purposes.

5. Clinical Impact and Efficacy of Radiation Reduction Techniques

In spite of these potential benefits, few studies to date document the clinical impact or efficacy of techniques to reduce radiation exposure in pediatric imaging. It is logical to assume that high-quality imaging with less risk of producing malignancy offers a definite advantage over relatively higher-dose techniques. Most of the research reported to date focuses on describing new technologies or detailing the dosimetric findings of reduced-dose techniques. Effectiveness results of reduced-dose techniques were found for chest CT, head CT, and lung scans. Predicted findings for real-time fluoroscopy, emergency room imaging, and abdominal CT are also discussed. (Mettler et al.2020)(Chandra et al., 2021)(Singh & Seed, 2020)

Chest CT studies show that the radiation dose can be reduced from the standard adult dose by 89-98% for chest diagnoses. Reports focusing only on head CT imaging describe decreased radiation from the adult head CT standard values by 38-80%. Lower-dose chest CT imaging for vascular ring workup can achieve a 96% reduction in radiation dose. In the past, a significant part of changing diagnostic protocols was the belief that more was better—more projections, reconstructions, or a higher radiation dose. This type of change is easy to justify to referring physicians or to the families of patients being imaged, since people easily understand the advantages of "more."

6. Future Directions and Emerging Technologies

Maintaining or enhancing diagnostic image quality while decreasing the radiation burden is an ongoing challenge in pediatric medical imaging. Technologic advances related to radiation reduction and optimization are rapidly evolving and require an understanding of both the current and future application of these methods by the pediatric radiologist, in part to address the unique physical and physiologic features of infants and young children. Emerging technologies that will be described include advanced statistical iterative image reconstruction, multienergy or spectral computed tomography, photon-counting computed radiography, model-based iterative reconstruction, and spectral attenuation correction techniques. Moreover, existing technologies, such as dual-energy digital radiography and tomosynthesis, are increasingly being applied at their tolerable radiation dose for pediatric imaging, further evolving our ability to reduce radiation exposure from these imaging modalities. These advanced technologies have the potential to improve disease detection and characterization while effectively reducing diagnostic radiation risks in pediatric patients. The possible future of pediatric medical imaging, including the versatility of advances in photonic detectors, is also discussed.

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التطورات في التصوير الطبي للأطفال: مراجعة لتقنيات تقليل التعرض للإشعاع:

مقدمة:

أصبح التصوير الطبي ضروريًا لتشخيص الأمراض وإدارتها، حيث يوفر مجموعة من التقنيات للحصول على صور للأعضاء الداخلية وأنسجة جسم الإنسان. لقد كانت التطورات في تقنيات التصوير هذه سريعة، مما أدى إلى زيادة مصاحبة في استخدام هذه التقنيات لتشخيص ومراقبة مجموعة من الأمراض لدى كل من البالغين والأطفال. يعتمد المتخصصون في الرعاية الصحية بشكل متزايد على التصوير الطبي لتحديد الأمراض الحادة، وتوجيه التخطيط والعلاج المقدم أثناء الإجراءات الجراحية، ومراقبة تقدم العلاج. على وجه الخصوص، يلعب التصوير دورًا حاسمًا في تحديد فعالية العلاج، وهو مطلوب لتحديد مدى وانتشار أورام العظام والأنسجة الرخوة قبل الخزعة أو العلاج الجراحي. وقد أثار استخدام التصوير الطبي لدى عدد متزايد من الأطفال، لا سيما في الأشعة التشخيصية، مخاوف في السنوات الأخيرة من أن التعرض المقابل للإشعاع المؤين لدى الأطفال مرتفع.

يشكل التعرض للإشعاع والمخاطر الناجمة عنه لدى الأطفال أساسًا للمخاوف بشأن الجرعة الفعالة التي يتلقاها المرضى من التأثيرات المسببة للسرطان المعروفة والمحتملة. بشكل عام، تتمحور هذه المخاوف حول مجموعتين من التقنيات: التصوير المقطعي المحوسب وفحوصات التنظير التداخلي. نظرًا لأن هذه التقنيات المنقذة للحياة تشكل الغالبية العظمى من جرعات الإشعاع المؤين للأطفال، فإن فوائدها ومخاطرها تحظى بأكبر قدر من الاهتمام. في حين أنها تمثل نسبة صغيرة فقط من جميع دراسات التصوير الطبي التي يتم إجراؤها، فإن فحوصات التصوير المقطعي المحوسب تحمل عبئًا فلسفيًا إضافيًا يتمثل في استخدامها بشكل متزايد لحالات غير مُشار إليها أو دون النظر في متابعة اختبارات بديلة. علاوة على ذلك، فإن المخاطر المحتملة هي دالة على الصحة المحددة للمريض والتاريخ العائلي للمخاطر الجينية. في الواقع، لا يزال الاستخدام غير المبرر لكل من تقنية التصوير المقطعي المحوسب وتقنية التنظير التداخلي يؤدي إلى زيادات مثيرة للقلق في الجرعة الجماعية للأطفال. على سبيل المثال، تم إجراء ستة ملايين فحص بالتصوير المقطعي المحوسب على الأطفال في الولايات المتحدة الأمريكية في عام 2003، مع تقدير تسعة ملايين فحص في عام 2005، ومن المتوقع إجراء 20 مليون فحص في عام 2006. مدفوعة بهذا الاستخدام المتزايد بسرعة، تُظهر أعداد متزايدة من السكان خطر الإصابة بالسرطان المرتبط بالإشعاع المؤين على الأطفال.