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Protecting sensitive patient groups from imaging using ionizing radiation: effects during pregnancy, in fetal life and childhood

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Abstract

The frequency of imaging examinations requiring radiation exposure in children (especially CT) is rapidly increasing. This paper reviews the current evidence in radiation protection in pediatric imaging, focusing on the recent knowledge of the biological risk related to low doses exposure. Even if there are no strictly defined limits for patient radiation exposure, it is recommended to try to keep doses as low as reasonably achievable (the ALARA principle). To achieve ALARA, several techniques to reduce the radiation dose in radiation-sensitive patients groups are reviewed. The most recent recommendations that provide guidance regarding imaging of pregnant women are also summarized, and the risk depending on dose and phase of pregnancy is reported. Finally, the risk-benefit analysis of each examination, and careful communication of this risk to the patient, is emphasized.

Keywords Pediatric radiology · Radiation protection · Computed tomography · Radiation-induced cancer · Child · Pregnancy

Introduction

The use of medical imaging in children has increased during the past few decades, raising concerns about risks associated with radiation. Reasons for the increased use of diagnostic medical radiation include the growing role of imaging in medical decision making as well as other factors such as defensive medicine. New techniques are now employed in medical fields where justification, optimization, quality assurance and training may need careful evaluation, such as use of cone-beam CT in dentistry. Existing techniques are becoming more widespread in non-surgical management, such as fluoroscopic interventional procedure. Modern CT systems have dramatically reduced radiation dose per examination, but today CT is a major source of medical radiation exposure in children and adults. 10% or more of CT examinations worldwide are performed for patients under the age of 18.

Managing exposure to radiation from medical imaging is a complex challenge; efforts that aim to reduce exposure in childhood include improvements in pediatric protocols, technological advances in equipment and implementation of diagnostic reference levels (DRLs).

European Directive framework

The new European Directive 2013/59/Euratom sets out basic safety standards for protection against the dangers arising from exposure to ionizing radiation and highlights the need for justification of medical exposure, requirements concerning patient information, quality assurance programs (recording and reporting doses from radiological procedures), the use of DRLs, the availability of dose-indicating devices and

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the improved role and support of the medical physics experts in imaging.

Article 61 of the European Directive 2013/59/Euratom [1] is focused on children, emphasizing that special attention will be paid to quality assurance programs and to the evaluation of the dose or verification of the activity administered for the practices involving medical exposure of children and to high doses procedures, which may be the case in interventional radiology, nuclear medicine, computed tomography or radiotherapy.

Article 62 of the European Directive 2013/59/Euratom states that if pregnancy cannot be excluded, depending on the medical radiological procedure, special attention shall be given to the justification and optimization, taking into account both the pregnant mother and the unborn child.

Factors that influence the risks of radiation

The biochemical and physiologic damage produced by radiation generally occurs within hours or days, but the impact of these changes, such as the induction of cancer, can take decades to manifest. This carcinogenic process has several steps. Aberrations in chromosomes are produced by DNA damage. Because these damaged cells survive, they become "stable aberrations," the first step to radiation-induced carcinogenesis. The second step is cellular immortality; that is, most cancer cells are descendants of a single cell that originally underwent neoplastic transformation. The third step is tumorigenicity [2].

Radiation exposures, like the medical ones, induce a cellular genomic instability that is transmitted to progeny, which was little described as "a persistent enhancement in the rate of which genetic changes arise in the descendants of the irradiated cells after many generations of replication… has been termed a 'non-targeted effect' of radiation, as genomic damage occurs in the cells that receive no direct radiation exposure" [3]. Most childhood tumors occur sporadically, but in 10–15% of the cases, a strong family association and genetic basis for radiation sensitivity are present, such as Li-Fraumeni syndrome or neurofibromatosis type 1, although the exact mechanism for this is unclear.

The effects of radiation are the greatest on rapidly developing tissues and organs—in fetuses, infants and young children [4]. In pregnancy, the major biological effects of fetal demise, growth restriction, organ malformations and cognitive deficits are seen only with doses in excess of routine diagnostic imaging [5]. Children are up to 10 times more sensitive than adults, and girls may be more sensitive than boys [2, 6]. However, Shuryak et al. recently noted that cancer induction risk (greater at younger ages) must be balanced with the radiation-induced promotion of premalignant damage (greater in middle age), which may vary according to cancer type [7].

Evolution of knowledge

Estimates of the carcinogenic risk of radiation are derived from epidemiological studies of large populations, such as the atomic bomb survivor cohort and nuclear industry workers and also from dose-response models, such as the linear no threshold (LNT) [8]. Diagnostic imaging uses low-level radiation that is defined, for the purposes of radiation risk, as < 100–150 mSv (i.e., < 20 mSv for a single-phase pediatric CT examinations). The U.S. National Academy of Sciences has commissioned a series of reports to study the health effects from exposure to low levels of ionizing radiation. These studies are referred to as the Biological Effects of Ionizing Radiation (BEIR) reports. The latest in this series of reports (BEIR VII report) provides evidence of a statistically significant increase in cancer incidence in survivors of atomic bombs in Hiroshima and Nagasaki receiving whole-body doses of 100 mSv or more, while the risks in the lower range are debated [9].

The LNT model is founded on the linear rapport supposition: radiation/mutation and cancerous mutation/cancer. A growing body of radiobiological evidence recently questioned the LNT model, indicating that cell and tissue damage may exhibit a low threshold dose [10].

According to Scott et al. [11], the LNT model is commonly adopted because it ensures a conservative approach (i.e., the model may overestimate the risk of cancer induction at low doses).

The radiation-induced clustering of DNA double-strand breaks into repair centers shows a nonlinear dose–response in human cells and is much higher at smaller doses, implying that LNT extrapolation could lead to overestimation of cancer risk in the low dose range [12]. The Life Span Study (LSS) cohort of about 120 000 subjects included atomic bomb survivors and residents of Hiroshima and Nagasaki who were not in either city at the time of the bombing. The aim of the study was to determine the late health effects of ionizing radiation derived from the atomic bombs. The resulting data only partially support the LNT model: cancer incidence decreased in the population exposed to radiation dose increases from 0.25 to 0.5 Gy, resulting in a significant curvature in the dose-response relationship [13].

New data from the updated SPAN (1958–2009) report that " the male risk in the LSS at 100 mGy using the linear quadratic Excess Relative Risk (ERR) model is estimated to be 0.01, lower than that of 0.047 scaled to 100 mGy from the INWORKS data (analysis of male nuclear workers in France, UK and US)" [14].

The Fukushima Health Management Survey estimated that the thyroid radiation doses in children were < 10 mSv in 95.7% of children (maximum: 33 mSv). Thus, reported external and internal radiation doses of residents in Fukushima Prefecture were less than 50 mSv. The Fukushima Health Management Survey will then contribute to future epidemiological research on nodular thyroid diseases in children and adolescents [15].

The risk associated with low doses is estimated to be small, such that it cannot be quantified accurately, as even very large studies would lack adequate statistical power to demonstrate small differences. In 2018, Bernier et al. published the preliminary results of the EPI-CT study ("epidemiological study to quantify risks for pediatric computerized tomography and to optimize doses") that recruited a total of about 950 000 patients who had undergone CT at least once before the age of 22 years [16]. When considering time since the exposure greater than 5 years, the cancer standardized mortality ratios (SMRs, i.e., the ratio between observed and expected number of deaths based on national reference rates) decreased to the level of the general population while the non-cancer SMRs remained significantly increased. These authors conclude that the study population was less healthy than the general population, and reverse causation bias should be considered for cancer risk analyses.

The American Association of Physicists in Medicine (AAPM) supports the position that when such exposures are medically appropriate, the anticipated benefits to the patient are highly likely to outweigh any small potential risks. In the position statement PP 25-C, AAPM declares that "at the present time, epidemiological evidence supporting increased cancer incidence or mortality from radiation doses below 100 mSv is inconclusive"…."and that any predictions of hypothetical cancer incidence and mortality from the use of diagnostic imaging are highly speculative … This may lead some patients to fear or refuse safe and appropriate medical imaging, to the detriment of the patient" [17]. Further, debate and research are fundamental to progress this area of science [18]. Increased radiosensitivity in children may be debated. In children's, developing organs mitoses are more frequent, and children have a longer life expectancy in which to express risk. However, cancer incidence does not increase linearly with mutation frequency, and cancer incidence significantly increases in old age. The huge increased risk of malignancies when the immune system is inhibited suggests that immune suppression may be one of the primary causes of cancers [19]. It may be hypothesized that low-dose radiation could enhance the immune system response and thus reduce cancer incidence overall.

Imaging dose optimization

There are no absolute defined limits for patient radiation exposure. However, it is reasonable to try to keep doses as low as possible or achievable (ALARA). One standard method is to follow dose reference levels for each examination procedure [20–23]. Two international campaigns aim to reduce exposure of children: (a) Image Gently [24] sponsored by the Alliance for Radiation Safety in Pediatric Imaging in the US and in 70 other countries around the World; (b) EuroSafe Imaging [25] sponsored by the European Society of Radiology (ESR).

Gonadal shielding

The use of gonadal shielding is debated. In general, the shielding should be correctly positioned under the pubic symphysis for males, centrally above the pubic symphysis for females. In males, the shielding is out of the acquisition plane, while in females, it is in the X-ray field. It must be remembered that, if the shielding interferes with any crucial structure, it is recommended not to use it.

Kaplan et al. [26] investigated on whether a gonadal shielding may affect the automatic exposure control (AEC) response. They showed that female gonadal shielding combined with AEC during pelvic radiography increases absorbed dose to organs with greater radiation sensitivity and to unshielded ovaries. The AEC should not be used in females because the shielding increases the exposure parameters considering the density of the irradiated structure.

Lee MC et al. [27] determined the incidence of missing or misplaced gonadal shields in pediatric orthopedic practice and determined the frequency with which visualization of bony landmarks is compromised by pelvic shielding. They concluded that 49% to 63% of pelvic shields were misplaced on standard pelvic radiographs, especially for girls. In addition, misplaced pelvic shields often obscured relevant pelvic or hip anatomy (in 0.3-51% of cases) contributing to a significant number of repeated radiographs.

Frantzen et al. [28] reported that the equivalent dose of radiation to the gonads with current imaging technology is approximately 0.008 to 0.098 mSv. Further, they reported that, because of the identified errors in misplacement of pelvic shielding and potential repeated imaging, pelvic shielding does not reduce the risk of radiation exposure for boys and potentially increases the risk of radiation exposure for girls.

Furthermore, Slovis and Strauss [29] highlighted how a significant fraction of the gonadal dose in both genders is from internal scatter, which is not attenuated by a properly placed gonadal shield. Assuming that with proper collimation, added filtration and technique selection, the gonadal dose without lead shielding from the examination should be 25–50 μGy for boys and 13–25 μGy for girls, the estimated increased risk from omitting gonad shielding is relatively small. These authors conclude that in order to lower the radiation dose, reducing the number of radiographs and teaching the proper collimation of images can have a greater effect than placing gonadal shields.

Radiation protection in fluoroscopy

Radiation reduction is not always appropriate because some examinations require multiple and additional projections, greater fluoroscopy time or magnification, or lower image noise to answer specific clinical questions. Implicit here is the "as low as reasonably achievable" principle, which entails using the amount of radiation necessary for diagnosis and no more. Planning includes clarifying with requesting physicians what the clinical question is, i.e., whether the radiation imaging test is justified, and also preoperative planning for efficiency can minimize dose during fluoroscopic and angiographic examinations.

A number of dose management strategies exist for fluoroscopy and interventional radiology, including those by the International Atomic Energy Agency and Alliance for Radiation Safety in Pediatric Imaging [30]. In addition, last-image hold, pulsed fluoroscopy, filtration, image store, video capture and alerts are part of examination optimization for children. Video recording during studies can provide review without use of additional fluoroscopy. Radiation exposure in fluoroscopy is widely variable across and even within different institutions, [31] hindered by lack of technical standardization.

The only fluoroscopic examination included in the PiDRL Report was the micturating cystourethrography, and no national pediatric DRLs have been set for interventional radiology procedures in any EU country to date [22]. DRLs for non-standard or newer life-saving interventional radiology procedures may be neither possible nor useful for more complex procedures.

ICRP 121 reports some key concepts to reduce dose during fluoroscopic examinations [32]. Time, shielding and distance are the three "platinum's" rules that have to be followed. First, fluoroscopy time should be limited. Pulsed fluoroscopy should be used and, in many instances, 3–8 pulses per second are adequate for guidance and monitoring of a procedure [33]. Still images acquired using last-image hold should be used to review findings instead of live fluoroscopy (repeated exposure).

The radiation field adjustments should be done with the light beam and not with the fluoroscopy function (X-ray beam). The anti-scatter grid should be removable and used normally for children over 8 years old, large younger children, or when very detailed images are required. Added copper filtration should be used (e.g., 0.3 mm) [30].

The fluoroscopy table should be positioned as far from the X-ray source as possible to reduce entrance dose to the skin, while the image intensifier should be as close to the patient as possible to minimize the image penumbra. Collimation of the X-ray beam is essential to reduce the exposed area and to keep radiosensitive areas (breast, eyes, thyroid and gonads) away from the X-ray beam, when possible. Magnification should be kept to a minimum as it increases the radiation exposure (post-processing images magnification is recommended, if possible). Finally, patient dose needs to be recorded and reviewed.

Interventional radiology procedures account for only 1% of X-ray procedures, but they are responsible of 10-15% of cumulative X-ray exposure. In interventional radiology, not only the stochastic risk, but also deterministic effects should be taken into account. Deterministic effects can be observed in the skin and, in neuroradiological interventions, to the lens of the eye and hair. Dose typically increases with serial exposures which may be proportional to the complexity and repeated exposure of the procedure. Suggested values for the trigger level for a deterministic effect are a skin dose of 3 Gy, a kerma-area product of 500 Gy cm2, or an air kerma at the patient entrance reference point of 5 Gy [34].

When the patient's radiation dose from the procedure exceeds the institution's trigger level, clinical follow-up should be performed for early detection and management of skin injuries.

Optimization of pediatric CT protocols

Relative to other imaging modalities, CT can provide a comparatively large dose of ionizing radiation. CT studies account for only 7–15% of all X-ray examinations in Europe but are responsible of 60–70% of the cumulative radiation exposure [35]. The number of CT examinations has been increasing rapidly, with children up to 15 years old undergoing approximately 11% of all CT examinations [36]. Technical innovations allowing faster examinations and better quality imaging have spread the use of CT in children in the last two decades [37].

Clearly, imaging modalities that do not depend on ionizing radiation, such as ultrasound or MRI, are realistic alternatives. When a CT examination is considered justified, the imaging technique should be optimized [38]. Several authors emphasize that attention shall be given not to reduce the CT dose too much: the real risk to the patient of an inadequate examination, either not yielding the correct diagnosis or needing to be repeated because it was non-diagnostic, is far greater than a small risk of latent malignancy [39]. MDCT scanners are now installed with default settings providing a "perfect" standard image and deliver the corresponding standard dose.

Optimization is a process by which a substantial portion of the standard dose is eliminated with a consequent increase in noise, but without loss in diagnostic performance and/or confidence. Several techniques can be adopted to reduce radiation dose to as low as possible, while still performing a diagnostic examination [40, 41]. A number of factors are involved in the optimization of CT protocols.

- Tube current: A reduction in tube current (mA) is directly related to an increase in image noise and the opposite. In general, larger patients require an increased tube current to prevent an unacceptable level of noise. However, very small children generally have less adipose tissue between organs and tissue planes and this can result in an excessive image noise related to tube current reduction and may need a proportional increase of the product of tube current and tube rotation time (s). Weight-based or girth-based protocols should be used when imaging pediatric patients, rather than age-based protocols.

Optimization includes consideration of the following factors:

- Peak kilovoltage: Increasing the kilovoltage (kVp) increases the energy of spectrum's photons, which results in a more penetrating X-ray beam. kVp has an exponential relationship with dose, and a decrease of 20 kVp will decrease the dose by about 35–40%. Lowering the kVp will also result in increased image noise, and an increase in mA is generally needed to maintain acceptable quantum mottle in the image. The choice of kVp depends on the clinical indication. A lower kVp generally improves bone detail and substantially increases contrast for CT angiography, while soft tissue studies without the use of a contrast agent are typically improved by increases in the kVp with appropriate reductions in the mA to result in reasonable patient doses [34].
- Pitch: A pitch of approximately 1.3–1.4 and a short rotation time (~0.5 s) to minimize total scanning time are generally recommended for pediatric body CT examinations. Cardiac studies require a faster rotation time and a lower pitch, thus resulting in increased patient dose.
- Automatic exposure control (AEC): This system is available in most modern scanners. The technique is based on the variation of the tube current according to patient thickness maintaining a predetermined level of quantum mottle decided by the operator. The improper use of AEC can result in increased patient dose or non-diagnostic examination [42].
- Patient positioning: Centering the patient's body in the isocenter of the CT gantry reduces the radiation dose to the patient. If the patient is not correctly positioned, the bowtie filters produce an inappropriate compensation of the X-ray beam resulting in more X-rays penetrating thinner peripheral portions of the patient's body and less X-rays penetrating in the central, thicker portion of the patient [43].
- Iterative reconstructions: This method processes several passes over the raw data (obtained using low-dose techniques) to produce more accurate model of images and to reduce the amount of noise [44]. This technique can reduce radiation as much as 40–80% while maintaining diagnostic quality [45]. Implementation requires time, careful adjustment of many acquisition parameters and diagnostic image acceptance.
- Clinical indication-based CT: Acceptable levels of image noise are not the same for all CT examinations. This changes according to the body site (i.e., imaging of the chest or skeletal system, can tolerate relatively increased noise, thus requiring a smaller dose, compared to brain, liver and other solid abdominal organs), and the clinical indications, including cumulative patient exposure. For example, a low-dose CT technique may be used to detect renal stones in children without compromising detection [46].
- Single-phase scan: A single-phase scan is generally all that is needed in pediatric imaging [41]. Unenhanced or delayed CT scans rarely provide additional information and should be reserved to specific indications. In order to reduce the dose, the length of the scout and the scan length should be limited to the clinical area of interest [47].

Radiation protection in pregnancy

Thousands of pregnant women are exposed to diagnostic radiation examinations each year. A misinformation on the radiological risks related to diagnostic examinations in pregnant or potentially pregnant women always causes anxiety in radiologists and patients and can lead to voluntary interruption of pregnancy.

Several well-recognized published documents provide guidance regarding imaging of pregnant women. The IRCP 84 [48] states that "Prenatal doses from most properly done diagnostic procedures present no measurably increased risk of prenatal death, malformation, or impairment of mental development over the background incidence of these entities." According to the same authors, there isn't any link between pre-conception irradiation of either parent's gonads and fetus malformations or childhood cancer. This evidence is based on atomic bombs survivors and survivors of childhood cancers treated with radiotherapy.

The American College of Radiology established that fetal doses below 100 mGy should not be considered a reason for terminating a pregnancy [49]. The American College of Obstetricians and Gynecologists [50] published the following policy statement: “Women should be counseled that X-ray exposure from a single diagnostic procedure does not result in harmful fetal effects. Specifically, exposure to < 5 rad (50 mGy) has not been associated with an increase in fetal anomalies or pregnancy loss.”

According to these documents, the risk to the unborn baby from radiation doses of < 50 mGy is negligible. Doubling that dose (i.e., 100 mGy), the increase over background incidence for organ malformation and the development of childhood cancer combined results in about 1%.

According to the International Commission on Radiological Protection, “prenatal doses from most correctly performed diagnostic procedures present no measurably increased risk of prenatal or postnatal death, developmental damage including malformation, or impairment of mental development over the background incidence of these entities; lifetime cancer risk following in utero exposure is assumed to be similar to that following irradiation in early childhood” [51]. However, there is no safe level: the ALARA principle requires that we use diagnostic methods without ionizing radiation whenever they are equivalent in reaching the diagnosis to those with radiation. The risks to the mother require justification, such as the proliferating breast gland that is more sensitive to radiation, or the metabolic adaptations to as well as anatomical changes of the pregnancy that may predispose to certain diseases, modifying indirectly the risks or benefits of a diagnostic imaging procedure. Knowledge of risks to the conceptus is limited and often has a wide range of uncertainty. Effects may be either stochastic or deterministic, with a rather high threshold [52].

While the natural risk for malformations at birth is 4%, 100 mGy of conceptus dose will only slightly reduce the proportion of children without a malformation from 96 to 95.8% [5], and similarly, the natural rate of 99.3% of children without a cancer during childhood will just marginally decrease to 99.07%.

In summary, after implantation of the conceptus in utero exposure by less than 100 mGy has no proven deterministic effects, but the stochastic effects of cancer induction, although small, are estimated to exist and to increase in proportion to the dose [53]. Deterministic effects exhibit a threshold of around 100 mGy even during the most sensitive phase of organogenesis.

The ALARA principle means that ultrasonography and magnetic resonance imaging and any non-imaging diagnostic examinations should be considered before X-ray imaging or nuclear medicine techniques are used. When ionizing radiation is appropriate, lower exposure is preferred to higher exposure as long as imaging quality is adequate to answer the clinical question.

The anatomical area exposed to direct radiation is the most important factor predicting the uterine dose.

In general, when performing a radiological examination in a pregnant woman, the clinical risk of not performing the examination must be evaluated. If the fetus is in the direct beam, the procedure should be tailored to reduce the fetus dose (i.e., for radiographic examinations: collimate the beam, increase kVp, remove the anti-scatter grid; for CT: collimate the beam and reduce the scan to the very specific area of interest). Fluoroscopic time must always be limited to the minimum [52].

Any department offering imaging services, beyond complying with general quality standards, has a number of duties regarding radiation exposure of pregnant patients.

Duties of a department of radiology, communication and decision

Duties of a Department of Imaging include information, screening for pregnancy, counseling, documentation and the decision for the best justified examination. Justification is based on the specific benefits and risks for both the mother and the child. The stronger the arguments for a critical situation of one of them are, the easier is the justification; in contrast, a vague suspicion would not justify an important exposure. Furthermore, each department clearly has legal responsibilities toward female staff members. While policies in different departments may differ slightly, it is important that each department formally states its rules in written form and follows them consistently.

Imaging the non-pregnant woman

Every adolescent girl and woman of childbearing age has to be considered as potentially pregnant and should be asked whether she is pregnant or thinks she could be [52, 54]. This may be supported by posters presented at the reception of the department, as suggested by the IAEA [55]. As the hormone level does not increase before implantation (with individual variation), it is suggested not to perform the test earlier than 10 days after ovulation; blood tests are more sensitive and, thus, become positive around 2 days earlier [56]. Patients below the age of 16/18 years pose an additional management challenge: they are both children under the responsibility of their parents and individuals with their own rights of privacy and discretion. Depending on the national legislation, the medical staff has a critical role of giving information to and accepting decisions and consent from the right person.

Imaging the pregnant woman

If pregnancy has been confirmed, justification will differ in the following three scenarios:

-Imaging without ionizing radiation and imaging of the extremities or the head and neck are justified as in non-pregnant women. As radiation exposure is absent or irrelevant, the examinations can be performed anytime.

-Imaging of the trunk of the body without direct radiation to the conceptus will cause some scatter radiation and a dose of well below 1 mGy to the conceptus. Examinations of this category will usually be performed when well-justified, but optimization becomes more important: the field of view should be minimized to the clinical question. It is critical that patients are well informed of the risk/benefit balance to avoid potentially declining an examination needed for immediate health. A medical physicist should calculate the conceptus dose for intermediate or high-dose examinations of the trunk with the potential of more than 1 mGy to the uterus, but not for examinations of the extremities or head. Termination of pregnancy should only really be considered for conceptus doses above 100 mGy, depending on the phase of pregnancy [50, 51].

Occupational exposure

The first duty of a department is to inform female workers of the existence and the risks of occupational exposure, the legal duties and rights, and to train them to behave correctly to minimize exposure [51]. International guidance and national laws clearly prescribe the exposure level allowed for a pregnant worker: as soon as she informs the employer of the pregnancy, the employer shall ensure employment conditions for the pregnant worker such that the "equivalent dose to the unborn child is as low as reasonably achievable and unlikely to exceed 1 mSv during at least the remainder of the pregnancy" [57].

How to communicate the risk

An effective communication with parents (or caregivers) and patients is crucial to ensure that the balance of risk vs. benefit is appropriate. Information should be available on the clinical utility and impact of the procedure or outcome. Alternative techniques and measures to reduce radiation exposure should be included in the discussion. The benefit of early diagnosis and treatment must be balanced with the current understanding of latent cancer risk, compared to the age of the patient and other comorbidities.

A recent WHO document helps support the discussion about benefits and risks of radiological examinations [58].

Comparison of the radiation exposure from a diagnostic examination with other radiation exposures (such as chest X-rays or natural background radiation) has been proposed as a tool to communicate with parents, but this system may be misleading; in fact, the dose of a chest X-ray is so low that comparing it with the level of dose of any other radiological procedure may be unnecessarily alarming. On the other hand, the concept of natural background radiation is not necessarily familiar to parents. Moreover, background radiation involves whole-body exposure, whereas diagnostic radiation exposures more often have regional (more localized) exposures.

A key concept that may help in the communication of the potential risk from radiological examination is that of the lifetime baseline risk (LBR) and the lifetime attributable risk (LAR).

The LBR is the general chance that everyone has of having a cancer and/or dying from cancer over the course of her/his lifetime. The LAR is the additional risk of premature incidence or mortality from a cancer attributable to radiation. The LAR is an age- and sex-dependent risk quantity calculated by using risk models derived from epidemiological studies.

Recently, Johnson et al. [59] calculated the LAR for cancer incidence for some specific radiological procedures in children, using the data from the BEIR VII report for the USA population. These are some examples of LBR and LAR [59]:

- Chest CT LBR 42%–LAR 42.15
- Abdomen CT LBR 42%–LAR 42.12
- Head CT LBR 42%–LAR 42.06%

Communicating the risk as the percentage increase of cancer incidence compared to the LBR (i.e., +0.15% for a chest CT; +0.12% for an abdomen CT or +0.6% for a head CT) could be an effective and non-alarming way to communicate the radiological risk.

Conclusion

Taking active steps to reduce the risk of ionizing radiation during pregnancy and childhood is imperative. These recommendations can help centers to reflect on their practices and improve them in line with EU guidelines.

Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animal performed by any of the authors.

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