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X-ray Radiation Risks in Pregnant Women: A Comprehensive Review of Medical Imaging Safety and Fetal Health Implications

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Abstract **Review Article**

This comprehensive review discusses the status of knowledge in regard to the risks associated with X-ray radiation when being undertaken during pregnancy with a primary focus on fetal safety, the courses of diagnostic imaging, and how clinicians navigate clinical decision-making regarding each case. The review explores peer-reviewed literature published between 2015-2025 in order to determine the potential of teratogenic effects caused by diagnostic X-ray procedures when undertaken during pregnancy. The consensus has led to the assertion, with current evidence suggesting, that diagnostic X-ray examinations undertaken as part of routine clinical practice can cause minimal risks to fetal development when individuals are exposed to radiation doses equal to less than or equal to 100 mSv, and in the case of most routine diagnostic procedures, the radiation dose should be less than respective to this amount. Nevertheless, the timing of exposure during pregnancy, cumulative radiation dose, and the anatomical region of the pregnant patient further influences the risk assessment. In considering risk assessment, the review promotes that the ALARA (As low as reasonably achievable) principle is incorporated into clinical practice and encourages medical practitioners to consider the role of imaging techniques (e.g., ultrasound, MRI) during pregnancy differently - as a safe course of imaging. To ensure a case-by-case basis, the clinical guidelines appeared to recommend assessing the risk and benefits as part of a documented dialogue and counseling with patients who are imminently planning to undergo diagnostic imaging during pregnancy. Overall, the findings point towards safe and evidence-based prescriptions related to medical imaging for pregnant individuals; the review considers impactful fear mongering and misunderstanding about radiation as a threat, which plagued the ability to proceed with the appropriate treatment/modalities when indicated and potentially resulted in the termination of wanted pregnancies.

Keywords: X-Ray Radiation, Pregnancy, Fetal Development, Teratogenic Effects, Diagnostic Imaging, Radiation, Safety.

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1. INTRODUCTION

Medical imaging is a vital part of healthcare today, and X-ray examinations are the most frequently provided diagnostic imaging investigation globally [1]. The field of diagnostic imaging during pregnancy is complex from the clinical perspective, as clinicians must weigh the medical necessity of the diagnostic information against the potential teratogenicity to the developing fetus. Notably, millions of women of reproductive age undergo X-ray examinations every year, making the issue of radiation exposure during pregnancy increasingly salient to medical practitioners, patients, and health care systems [2]. Although the fear of radiation exposure during pregnancy is not unfounded, ionizing radiation can cause biological damage to developing tissue, and it is possible that the fetus is more sensitive to radiation effects due to the rapid dividing cells and the process of organogenesis that occurs in early growth and development. The potential for biological damage during pregnancy has encouraged research to investigate the relationship between exposure to diagnostic radiation and fetal outcomes. The results of this type of research have had an impact on changing guidelines and protocols and ensuring safety [3]. The available medical literature provides more nuanced information on radiation risks during pregnancy with evidence that the actual risks from diagnostic X-ray procedures are much less than are typically perceived by both

patients and clinicians. Physician reported perceptions of the teratogenic risks of radiographic examinations, compared to what is evidenced based teratogenic risk, are often exaggerated even to the point of causing delay in diagnosis and patient concern [4].

The advancement of imaging modalities beyond x-rays, including ultrasound and magnetic resonance imaging (MRI), has allowed for safer chances in many clinical scenarios involving pregnant patients; however, there are scenarios where x-ray diagnostics is still required in emergencies, or other diagnostic situations where there is limited alternative, or a non-suitable one; therefore, it is still immovably of importance to comprehend dosage risks coupled with safety measures undertaken, and evidence-based practice [5]. The purpose of this review is to summarize what we know about the risks of X-ray radiation to pregnant women, including biological pathways of radiation injury, human studies that provide clinical evidence, models of risk assessment, and considerations for practice for healthcare providers. The review will also contend with common misperceptions about radiation risk, while delivering evidence-based guidance on how to facilitate informed clinical care, decision-making around obstetric patients, and patients in other emergent circumstances.

2. THEORETICAL FRAMEWORK OF X-RAY RADIATION AND BIOLOGICAL EFFECTS

X-ray radiation is a part of the electromagnetic spectrum and possesses sufficient energy to remove electrons from atoms and create ions in biological tissues. This ionization process is the basis for the use of X-rays for diagnostic purposes and the potential biological effects of X-rays. X-rays can interact with matter and causes by producing directly cellular damage, the damage is often to the most important biological molecule, DNA or indirectly by producing free radicals that will then damage a biological molecule [6]. There are several factors involved with the biological effectiveness of ionizing radiation dosimetry such as, the total dose of radiation absorbed, the dose-rate, the quality of radiation (the type/nature), and the sensitivity of the irradiated tissue. The radiation dosage is generally given in Gray (Gy), when considering the energy deposited per unit mass of tissue. The biological effectiveness is given in Sievert (Sv), which considers the relative biological effectiveness of each of the different types of radiation [2].

The developing fetus is particularly sensitive to ionizing radiation for a variety of reasons. Embryonic and fetal development are characterized by rapid cellular division, which increases the likelihood of radiation inducing DNA damage, and the developing fetus is less efficient at repairing damaged DNA in its early stages of development. The developing embryo is much smaller than the adult tissues and, therefore, for any given exposure, there is a greater dose per unit mass to the embryonic tissues than the adult tissues [5]. Radiation effects on the fetus can be divided into deterministic (threshold) effects, and stochastic (probabilistic) effects. Deterministic effects (e.g., growth restriction, malformations, neurological dysfunction), are only seen above some threshold dose of radiation and become more severe as dose increases, these effects are most important during organogenesis (which typically occurs between 2- 15 weeks of gestation) [3]. Stochastic effects, on the other hand, include cancer induction and genetic mutations, no threshold of radiation is apparent and stochastic effects can result from any dose of radiation, and are thought to increase probability in a linear fashion with dose. The fetus' vulnerability to radiation is highly variable with gestational age and differs because the fetus is developing different structures at each gestational age. The pre-implantation phase (0 - 2 weeks post-conception) has an "all-or-nothing" response in terms of radiation exposure; either the result is embryonic death or there are no observable effects of the radiation exposure. The organogenesis phase (2 - 15 weeks) is the time period that has the highest concern for radiation-related malformations, especially affecting the central nervous system, cardiovascular system and grossly, limb malformations. The focus during the fetal period (15 weeks to term) remains on growth restriction and neurodevelopment. The central nervous system is particularly vulnerable to the effects of radiation during this stage of pregnancy, with the risk of radiation-induced intellectual disability persisting through the second trimester. Understanding these important periods can assist with risk analysis and clinical decision-making pertaining to medical imaging in pregnancy [7].

3. DOSE-RESPONSE RELATIONSHIPS

There has been considerable research establishing dose-response relationships for many of the radiation effects during pregnancy [1]. For deterministic effects, certain threshold doses are designated. Growth restriction can occur as early as tissues are exposed to doses exceeding 100-200 mSv, while malformations and severe neurological effects typically occur at doses above 200-500 mSv. These thresholds are substantially higher than the dose delivered by routine diagnostic X-ray procedures, which typically deliver doses in the range of 0.01-10 mSv. Stochastic effects follow a linear no-threshold model, which means any dose of radiation, regardless of the size, has a risk of causing some kind of cancer induction. When considering the absolute risk increase associated with exposure to diagnostic radiation, it is minimal. In the example referenced, fetal doses less than 100 mSv were estimated to increase the likelihood of childhood cancer by a 0.1% risk increase (increased risk of childhood cancer risk from a baseline approximately 0.2-0.3%) [8].

4. CLINICAL EVIDENCE AND RISK ASSESSMENT

Large epidemiological studies have provided some important evidence regarding the actual risks of exposure to radiation from diagnostic X-rays during pregnancy. The studies of survivors of the atomic bombs dropped on Hiroshima and Nagasaki, although involving doses of radiation much higher than would be involved in diagnosis, demonstrated the general doseresponse relationships for radiation and pregnancy. Things like severe deterministic effects from radiation do occur at much higher doses than seen in diagnostic radiology [3]. More applicable to practice are the studies looking at the clinical evidence of consequences of diagnostic radiation exposure. A

pooled analysis of more than 1.8 million pregnancies (Morrell et al. 2002), found no increased risk of major malformations, restriction of growth, or perinatal mortality, found no increased risk after diagnostic X-ray examinations during the pregnancies or previous pregnancies. The studies thus far, on prenatal exposure to CT have similarly found no evidence for an increased risk of teratogenicity, with doses encountered in clinical practice [5]. Radiation doses to the fetus vary based on the X-ray examination, which ultimately affects risks, and related clinical decision making. Chest X-rays are the most commonly performed radiographic examination, and it has low fetal doses (usually less than 0.01 mSv) because of the distance between the fetus and uterus from the X-ray beam, and use of proper shielding. Therefore, even if an individual had multiple chest radiation during pregnancy there would very little risk for fetal development [8]. Abdominal and pelvic radiograph has a direct exposure to the uterus and fetus producing a higher, but can be considered low dose (usually 1 to 10 mSv). The situation may be acute or emergencies, and numerous exams take place subsequently (or CT scans); at that time the combined dose may reach 50-100 mSv. Those levels would be below the reliable threshold for deterministic effects, but would likely merit more reconsideration and counselling [9]. CT imaging gives radiation doses higher than standard x-ray doses, with abdominal scans typically exposing the fetus to approximately 10-50mSv. Emergency CT imaging during pregnancy can be unavoidable in some circumstances, particularly in trauma patients or when evaluating potential appendicitis or other acute abdomen conditions. Good news is studies that evaluated pregnancy outcomes after CT exposure have not demonstrated any increase in major malformations or adverse pregnancy outcomes [4]. Use of dose reduction strategies that include automatic exposure control, iterative reconstruction algorithms, and the optimized application of protocols with pregnant patients significantly decrease fetal doses (doses that are still considered low compared to lower limits for motivation). Modern CT imaging has optimizable equipment that allows for substantially lower doses in comparison to previous years and offers improved safety profiles for pregnant patients [7,8]. Ultrasound and MRI are safer alternative imaging modalities for many clinical indications in pregnancy compared to the use of X-rays. Ultrasound can be marketed as the safer imaging modality, as it uses non-ionizing acoustic energy and there are no known harmful effects to protect a developing fetus. Ultrasound is also the primary imaging modality provided to obstetric patients. MRI has better soft tissue contrast than US and is appropriate as long as the MRI examination time does not exceed MRI limits to developing fetuses and there is no ionizing radiation exposure. MRI has higher costs and longer exam times, but can be used when US cannot be used or cannot determine the diagnosis or to compliment US [2,7]. The most appropriate imaging options are based on clinical indications, urgency of diagnosis, and resource availability. Emergency situations may require X-ray examinations when other alternatives are insufficiently adequate or unavailable. Health care providers should know the strength and limitations of each imaging modality based on clinical indications and what is needed [2].

5. RISK COMMUNICATION AND PATIENT COUNSELING

Making effective risk communication entails putting radiation risks into context with other pregnancy-related risks. The baseline risk of major malformations in the general population is about 2-3%, which exceeds the risk of exposures that have a higher risk of malformations from diagnostic radiation exposure. Studies show that many health providers grossly overestimate the risks of radiation exposures, which can lead to the risk of inappropriate counseling and unnecessary anxiety [9]. Patient counseling ought to stress that routine diagnostic X-ray examinations pose minimal risk to the developing fetus, as the risks are minimal compared to risks from other concerns related to pregnancy. Explaining the threshold doses, deterministic effects and stochastic effects should be done using lay terms. When patient counseling occurs, it also provides opportunities for medicolegal documentation of counseling discussions, and a documented process of informed consent in the completed report. Documented and informed consent provides some medicolegal protection if an incident occurs after the patient underwent imaging. In addition, documentation of the informed consent process demonstrates quality assurance of the practitioner's medical practice.

6. THE ALARA PRINCIPLE

In pregnancy, the basis of the principle governing radiation risk is ALARA (As Low as Reasonably Achievable) which basically encourages the practitioner to reduce the dose of radiation while maintaining the examination to be diagnostically effective. This consists of aspects such as demonstrating justification for the examination, optimizing the technique, and limiting the radiation dose with use of shielding and limiting to the part of the body to be imaged [10]. In order to implement ALARA, the practitioner must take into account the clinical indications for imaging, the different imaging modalities available in the healthcare setting and, as a safeguard, must optimize technical parameters. We always have to consider the potential benefit associated with diagnostic information against the very small (but not negligible) risk associated with radiation exposure. This will require appropriate input from multi disciplinary sources where indicated.

7. PROTOCOLS AND QUALITY CONTROL

Healthcare organizations should develop written protocols for management of pregnant individuals requiring a radiological examination. Each protocol should include protocols for pregnancy screening, alternative non-ionizing imaging options, and dose optimization protocols, and counselling protocols. Regular education of the healthcare worker related to radiation safety and measures associated with pregnancy suggests the need for well prepared educational initiatives in protocols development. Quality assurance programs should know the actual radiation doses delivered to pregnant patients, register the pregnancy outcomes when available, and formally audit compliance with protocols. Protocols should be reviewed and updated regularly, in view of

the emergence of new evidence or new technology, to ensure they reflect the best in patient care [10].

8. CONCLUSIONS

This systematic review of current literature shows that hazards related to X-ray radiation in pregnant women is much less than widely held views by healthcare professionals and their patients. Diagnostic X-ray procedures pose low risk to fetal development when a physician has indicated the examination is necessary. The doses involved are also usually under or far below threshold doses where deterministic effects occur. Overall, there is adequate evidence to indicate that routine diagnostic radiographic examinations during pregnancy involving X-rays are safe when precautions are taken and the dose is optimized. In summary, the following findings are derived from this review: threshold doses for major malformations and growth restriction (100-500 mSv) are much greater than what is delivered when exposure on the hundreds of examinations delivered by X-rays (10 mSv or less). Epidemiological studies have consistently shown that adverse pregnancy outcomes do not follow occupation use of diagnostic radiation at clinically relevant and low doses. There are periods of pregnancy that are more important than others in terms of potential organ malformation (2-15 weeks) and organogenesis reduces the risk. The reasonably low risk involved with the use of diagnostic therapeutic radiation on pregnancy and clear articulation of the principles of ALARA in the context of providing the best practical imaging strategies toward patient care/safety makes for a clearer decision making framework for clinical interpretation. While the risk of ionizing radiation exposure is negligible, the consideration of the substantial value of diagnostic information and significant benefits of health outcomes of the mother and/or fetus should be more of significance than the risk associated with diagnostic imaging, especially in situations where delaying a diagnosis would have potentially serious impacts on maternal and/or fetal health.

9. RECOMMENDATIONS

Several recommendations can be made from the currently available evidence, for clinical practice. First, diagnostic any x-ray examinations should not be withheld from a pregnant patient, when truly relevant. In most medical scenarios, the risk of not diagnosing and/or delaying diagnosis tends to exceed the risks associated with the minimal radiation dose to the fetus. Second, all health care providers should be educated with respect to the actual radiation risks vs perceived risks, to assist with their clinical decision making and patient counseling. It is abundantly evident that a large volume of physicians seriously overestimate the radiation risks associated with RD exposures, which has a detrimental effect on patient care. Third, if clinically appropriate and available, imaging modalities such as ultrasound and/or MRI may be the preferred modalities, however, be mindful of not delaying imaging unnecessarily when x-ray examinations are required urgently. Fourth, health institutions should develop a protocol for all rad applications on pregnant patients; including pregnancy screening, committed doses, and the process for patient counseling. Finally, research is required to expand the current knowledge of radiation risks for pregnant patients. with respect to low dose exposures and long-term effects of exposure. With the introduction of dose reduction strategies, and improved communication of risks to patients, will only enhance patient safety, and also quality of care.

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