



Fetal Dose in CT Scans During Pregnancy

Hamilelikte BT ile Fetal Doz Değerlendirmesi

Ümit KARA ^{1*}

¹Süleyman Demirel University, Isparta Health Services Vocational School, Turkey

*Corresponding author: umitkara@sdu.edu.tr

ABSTRACT

Objective: In cases where computed tomography (CT) scans are clinically necessary for pregnant patients, accurately estimating fetal radiation exposure is essential. Current methods, however, lack practicality for routine clinical use. This study aims to calculate fetal and organ doses in pregnant patients undergoing CT scans using the Monte Carlo Simulation Method. **Methods:** Monte Carlo (MC) simulations were conducted on phantoms representing pregnant patients at gestational ages of 8-15 weeks, using a 64-slice CT scanner (Discovery CT750 HD GE Healthcare). Organ doses were also calculated. The MC code for dose distribution was validated through CT Dose Index (CTDI) measurements, following AAPM protocols. Volumetric CTDI values were normalized, developing an algorithm for fetal dose estimation across various body regions and exposure settings. **Results:** Fetal doses were within safe limits, indicating minimal risk to development. The study highlights the importance of minimizing radiation exposure, particularly through low-dose protocols. Additionally, optimizing CT parameters and using alternative imaging methods, such as ultrasound or MRI, are recommended when clinically feasible. **Conclusions:** This study presents a practical approach for estimating fetal radiation doses during CT scans, aiding in exposure reduction. Future research may expand this algorithm's validation across larger patient groups, emphasizing the need for radiology practices to employ the lowest dose possible and to consider non-ionizing imaging alternatives.

Keywords: Monte Carlo Simulation, Fetal Radiation Dose, CT in Pregnancy, Low Dose Protocols

ÖZ

Amaç: Travma veya klinik fayda gerektiren diğer durumlarda, gebe hastalarda bilgisayarlı tomografi (BT) taramaları gerektiğinde, fetüsün maruz kaldığı radyasyon dozunu doğru tahmin etmek önemlidir. Ancak mevcut yöntemler, rutin klinik kullanım için pratik değildir. Bu çalışma, Monte Carlo Simülasyon Yöntemi ile gebe hastalarda BT taramalarından kaynaklanan fetal ve organ dozlarını hesaplamayı amaçlamaktadır. **Yöntemler:** Farklı gebelik dönemleri (8-15 hafta) için gebe hasta fantomları kullanılarak 64 kesitli BT tarayıcı (Discovery CT750 HD GE Healthcare) ile Monte Carlo (MC) simülasyonları gerçekleştirildi. Organ dozları da hesaplandı. AAPM protokollerine göre BT Doz İndeksi (CTDI) ölçümleriyle doğrulanan MC kodu, hacimsel CTDI değerleri normalize edilerek fetal doz hesaplamalarında kullanılmak üzere bir algoritma geliştirildi. **Bulgular:** Fetüsün düşük radyasyon dozlarına maruz kaldığı ve bu seviyelerin fetal gelişim için risk oluşturmadığı gözlemlenmiştir. Çalışmada elde edilen dozlar, kabul edilebilir klinik sınırlar içerisindedir. Düşük doz protokollerinin kullanımı ve BT tarama parametrelerinin optimizasyonu, gebelikte radyasyon maruziyetini en aza indirmede etkilidir. Uygun olduğunda, ultrason veya MRI gibi iyonlaştırıcı olmayan alternatif görüntüleme yöntemleri önerilmektedir. **Sonuçlar:** Bu çalışma, BT taramaları sırasında fetal radyasyon dozlarını hesaplamak için uygulanabilir bir yaklaşım sunmaktadır. Geliştirilen algoritma, fetal maruziyeti azaltmada önemli bir araç olabilir. Gelecek çalışmalar, algoritmayı daha geniş hasta gruplarında doğrularak araştırmayı genişletebilir ve düşük doz protokollerinin önemini vurgulamaktadır.

Anahtar Kelimeler: Monte Carlo Simülasyonu, Fetal Radyasyon Dozu, Gebelikte BT, Düşük Doz Protokolleri

INTRODUCTION

Computed tomography (CT) is an established imaging modality in modern medicine that delivers rapid and high-resolution images for diagnostic and therapeutic purposes. The use of CT imaging has significantly increased over the past few years, particularly in certain populations like pregnant women, due to trauma injuries, cancer screenings, and other clinical applications (1). Because CT provides fast and accurate diagnostic information, it is often preferred in emergency situations, even for pregnant patients. However, the ionizing radiation involved poses risks, especially to radiosensitive tissues like the fetus (2).

The biological effects of ionizing radiation, such as DNA damage and cell death, are well-known and linked to cancer development (9). The developing fetus, especially during rapid cell division, is highly sensitive to radiation, leading to risks like developmental abnormalities, organ malformations, and a higher risk of cancer later in life (3). Thus, it's crucial to carefully assess radiation risks for both the mother and fetus during CT scans (4). Ideally, alternative imaging methods without radiation exposure, like ultrasound or MRI, should be used whenever possible. But in emergencies, where CT is necessary, the diagnostic method with the lowest possible radiation dose for both the mother and fetus should be selected (5).

The fetus's susceptibility to radiation depends on factors such as gestational age, patient anatomy, the distance between the uterus and the scanned region, and CT scan parameters (4). For instance, fetal doses from scans of the mother's neck or head are negligible, while direct scans involving the uterus may result in doses up to 50 mGy (6), which can significantly affect development.

Existing methods to estimate fetal radiation exposure during CT have practical limitations in clinical practice, often lacking accuracy or feasibility across different scenarios. Thus, there's a need for more reliable and clinically applicable models that can be easily integrated into workflows. Since radiation impacts rapidly dividing cells, such as those in a developing fetus, accurate fetal dose estimation during CT is critical to assess these risks. However, direct measurement is technically and ethically challenging (6), necessitating dependable models (7).

One of the most reliable ways to assess fetal radiation exposure is through Monte Carlo simulations. These simulate the interaction of photons and ionizing radiation with body tissues to provide accurate radiation absorption estimates (8). This method is widely used in pregnant patients through patient-specific models and phantoms. For example, Angel et al. (6) employed Monte Carlo simulations to estimate fetal doses at different gestational stages. These methods offer reliable dose estimations, yet further refinement is needed to integrate these results into real-time clinical decisions.

In conclusion, minimizing radiation risks for pregnant patients undergoing CT scans requires reliable dose estimation methods. Monte Carlo simulations and other modern techniques play a crucial role in this context (8). This study aims to calculate fetal radiation doses accurately using the NCICT simulation tool and emphasizes the clinical applicability of Monte Carlo methods. Additionally, it seeks to address the limitations of current fetal dose estimation practices by providing healthcare professionals with a validated tool.

MATERIAL and METHOD

This study employed the NCICT dosimetric simulation tool, which leverages a Monte Carlo-based approach, to precisely estimate organ doses in pregnant patients and fetuses undergoing CT scans (8). The NCICT system is specifically designed to simulate radiation exposure across various organs and calculate effective doses during CT imaging, providing detailed information critical for dose management in clinical settings (6). In this study, the tool was optimized to enhance its accuracy and applicability in assessing organ doses specific to pregnant patients and their fetuses (4).

Patient-specific data was incorporated to allow for realistic dose assessments in both pregnant individuals and their fetuses (5). Anthropomorphic models were selected to represent pregnancy stages between 8 and 15 weeks, capturing the natural anatomical changes occurring during early gestation. These models were sourced from the comprehensive NCICT database, ensuring that the simulations closely aligned with real clinical scenarios and reflected the unique anatomical characteristics of pregnant patients at each gestational age (3,8). The models were further adapted for use with the NCICT system, including adjustments to better represent pregnancy-specific anatomy, thus enhancing the fidelity and relevance of the simulation outcomes (6).

Simulation process, Monte Carlo simulations integrated within the NCICT framework enabled in-depth radiation dose calculations at the organ level. This method involves tracking the interactions of photon particles as they pass through different tissues, which is essential for accurately estimating energy deposition in radiosensitive areas such as the uterus and fetal organs. By incorporating a Python-based backend, the simulations were streamlined for efficient processing, which facilitated scalability and allowed for multiple patient models and CT scan protocols to be simulated with precision (6).

Detailed Steps for Dose Calculation: CT Scan Parameters Input: A Python-based interface was developed to input essential CT scan parameters, including tube voltage (kVp), tube current (mAs), scan length, pitch, rotation time, and scan mode (e.g., spiral or helical). These parameters were chosen based on clinical protocols typically used in diagnostic CT imaging for pregnant patients, ensuring that the simulations could replicate real-world clinical scenarios accurately (6). The choice of these parameters is critical, as variations can influence radiation dose and distribution, especially in sensitive anatomical areas.

Selection of Patient Models: Anthropomorphic models tailored for various gestational stages (8-15 weeks) were selected from the NCICT database. Each model represents specific anatomical characteristics associated with the given gestational period, reflecting changes in maternal and fetal anatomy. Python-based functions automated the model selection process, ensuring that the appropriate model was applied based on the patient's gestational age, allowing for an accurate assessment of radiation exposure relative to gestational development (8).

Monte Carlo Photon Simulations: In these simulations, photon interactions with tissues were simulated in detail, with each organ assigned specific absorption coefficients to determine the likelihood of photon interaction and energy transfer. The simulations were designed to focus on energy deposition within radiosensitive organs, such as the uterus, fetal brain, liver, and other critical organs, ensuring that radiation exposure estimates were as accurate as possible. Monte Carlo techniques accounted for variations in tissue composition, organ density, and anatomical location, providing a realistic representation of radiation distribution within the body (4).

Calculation of Organ Doses: Energy absorbed in each organ was converted into radiation doses, expressed in milligrays (mGy). This conversion involved calculating the absorbed dose for each organ based on the number of photon interactions, the energy deposited, and the organ's size and density. The results were then evaluated according to national and international radiation safety standards, specifically those outlined by the International Commission on Radiological Protection (ICRP) and the American Association of Physicists in Medicine (AAPM). These standards provided reference values to ensure that radiation exposure remained within clinically safe limits, particularly for vulnerable fetal tissues (9).

Validation of the Monte Carlo simulation results was conducted by comparing calculated doses with CT Dose Index (CTDI) measurements obtained in accordance with AAPM protocols (9). CTDI values serve as a standard metric for assessing radiation output from CT scanners, and aligning the simulation data with these values ensures consistency with clinical dosimetric

benchmarks. Additionally, comparisons were made with established dosimetric data from the literature, verifying the accuracy and reliability of the calculated doses. This validation process confirmed that simulated doses fell within acceptable error margins, underscoring the robustness of the Monte Carlo method in providing reliable estimates of fetal and maternal radiation exposure during CT scans (6).

Validation is crucial as it ensures the fidelity of the simulation tool, allowing healthcare professionals to confidently use these estimates in clinical decision-making.

Table 1: Summary of the CT Protocol Parameters

Parameter/Process	Discovery CT750 HD - Brain Scan	Discovery CT750 HD - Thorax Scan
Scan Type	Brain	Thorax
Rotation Time (s)	0.5	0.4
Detector Configuration (mm)	20	40
Table Speed (mm/rotation)	10.62	55
Tube Current (mA)	200	200
Tube Voltage (kVp)	100-120	100-120
Automatic Exposure Control (AEC)	Off	Off
Scan Field of View (SFOV)	Brain	Thorax
Reconstruction Algorithm	Standard	Standard
CTDIvol (mGy)	38.43	15
Description/Components		
Input	CT Scan Parameters Entry	-kVp (tube voltage) -mAs (tube current) -Scan length -Pitch -Rotation time -Scan mode (spiral/helical)
Model Selection	Anthropomorphic Model Selection	-Gestational age (8-15 weeks) -Maternal anatomy models -Fetal anatomy models -Organ-specific parameters
Simulation	Monte Carlo Photon Simulation	-Tissue-specific absorption coefficients -Energy transfer calculations -Radiosensitive organ focus -Anatomical variation accounting
Calculation	Organ Dose Calculation	-Energy absorption quantification -Dose conversion to mGy -Organ-specific dose estimation -ICRP/AAPM standard comparison
Validation	Results Validation	-CT Dose Index (CTDI) measurements -Literature data comparison -Error margin assessment -Clinical benchmark alignment
Output	Results Visualization and Reporting	-Organ dose tables -Visual dose distribution maps -Fetal dose estimation -Clinical recommendation support

RESULTS

This study examined the organ doses for a pregnant woman during head CT scans performed at 8 and 15 weeks of gestation using Monte Carlo simulations. The results indicated comparable radiation doses between both gestational weeks, with slightly higher radiation absorption at 120 kVp compared to 100 kVp. The specific organ doses and their clinical relevance are discussed below.

Brain: While the brain is relatively resistant to radiation, the doses observed in this study (ranging from 37.67 mGy to 40.92 mGy) should be carefully considered, especially in pregnant patients. There are no immediate short-term effects linked to these doses, but long-term cumulative exposure may elevate neurological risks. CT scans during pregnancy are particularly important for fetal neurological development. The higher doses at 120 kVp, compared to 100 kVp, show that more radiation is absorbed at higher tube voltages.

Pituitary Gland: This critical endocrine organ, responsible for hormone production, was exposed to doses between 32 mGy and 36 mGy. These levels are of clinical concern, as radiation exposure to the pituitary during pregnancy could disrupt maternal hormonal balance, potentially affecting fetal development. Hormonal changes caused by radiation may have long-lasting effects on pregnancy outcomes.

Lens: The eye lens is highly sensitive to radiation, with doses in this study ranging from 45 mGy to 46 mGy. These levels are known to increase the risk of cataract formation, a condition resulting from cumulative radiation exposure. Therefore, such radiation levels should be monitored closely, particularly due to the cumulative nature of lens damage.

Eyeballs: Radiation exposure to the eyeballs was recorded at 44–45 mGy, approaching the threshold for eye health. While immediate risks are minimal, the long-term effects on sensitive eye tissues must be taken into account.

Salivary Glands: The salivary glands received relatively high doses (46–48 mGy), and prolonged exposure could lead to reduced saliva production, dry mouth, and potential loss of function. Monitoring radiation exposure to these glands is vital to prevent long-term damage.

Oral Cavity: Radiation doses to the oral cavity ranged from 36 to 39 mGy, posing a moderate risk to mucosal tissues. These doses may result in symptoms like mucosal damage and dry mouth, necessitating close monitoring in clinical settings.

Spinal Cord: Although significant radiation to the spinal cord can result in neurological issues, the doses observed in this study were low (4.45–4.91 mGy), and are unlikely to cause clinical effects. However, low-dose protocols should be maintained to minimize any potential risk.

Thyroid Gland: The thyroid, one of the most radiation-sensitive organs, was exposed to doses between 3.67 mGy and 3.98 mGy. Even low doses can increase the risk of thyroid cancer, so radiation to this area should be minimized whenever possible. Protective measures like thyroid shielding are recommended.

Other Organs (Esophagus, Trachea, Thymus, Lungs, Breast, Heart Wall): These organs were exposed to relatively low doses (0.7 to 10 mGy). While these doses are within acceptable limits for less sensitive organs, their long-term impact on critical organs, like the heart and lungs, should not be overlooked, especially in cases of repeated exposure.

Effective Dose: The effective dose, used to assess the overall impact of radiation exposure on health, ranged from 1.8 mSv to 1.95 mSv in this study. These values fall within acceptable limits for a CT scan. However, cumulative exposure to radiation over time still poses risks such as cancer.

Therefore, keeping radiation doses "As Low As Reasonably Achievable" (ALARA) is critical. Although the differences between 100 kVp and 120 kVp were minimal, slightly higher doses were observed at 120 kVp. This indicates that higher tube voltages lead to greater radiation absorption in organs. Radiation doses to sensitive organs like the eyes, thyroid, and salivary glands reached clinically significant levels, which requires careful consideration in clinical protocols. Although effective doses were within safety limits, the potential long-term effects on the fetus, especially concerning cumulative exposure, should not be ignored. Whenever possible, lower-dose protocols or alternative imaging methods, like MRI or ultrasound, should be preferred.

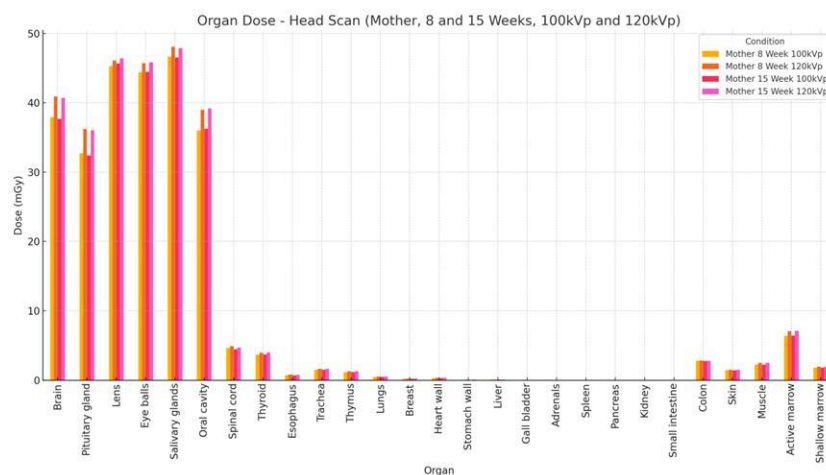


Figure 1: Mother Gestational Age (8-15 Weeks) Phantom with Different kVp Organ

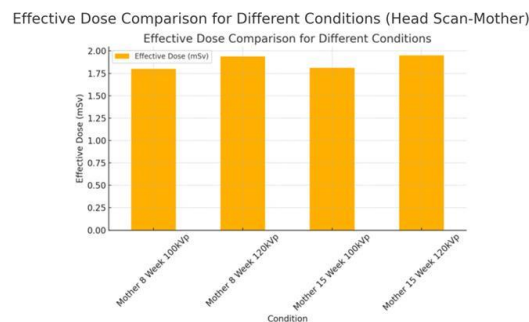


Figure 2: Mother Gestational Age (8-15 Weeks) Phantom with Different kVp Effective Doses Organ

The fetal organ doses for head CT scans at 8 and 15 weeks of gestation. The results indicate that no significant radiation exposure was observed in critical fetal organs such as the brain, pituitary gland, eye lenses, and eyeballs. This is a positive outcome, as it shows that these radiation-sensitive organs were effectively protected during the scans. The absence of radiation exposure to the brain and eye lenses is crucial for the fetus's long-term neurological and visual development. At 8 weeks of gestation, the salivary glands and oral cavity received minimal radiation doses (0.01 mGy). These doses are extremely low and pose no clinical risk. At 15 weeks, no radiation was detected in these organs, reinforcing the conclusion that the overall exposure to the fetus was negligible.

For the spinal cord, doses ranged between 0.01 and 0.02 mGy. While the spinal cord is a vital structure, these radiation levels are so low that they are unlikely to cause any significant effects, such as nerve damage. The low radiation doses observed suggest that the developing nervous system was well protected.

The thyroid gland, known for its sensitivity to radiation, received doses ranging from 0.01 to 0.05 mGy. While radiation exposure to the thyroid carries the risk of thyroid cancer, the extremely low doses recorded in this study are considered low-risk and are unlikely to affect thyroid health adversely. The lack of radiation exposure to the thyroid early in pregnancy is a favorable outcome, reducing the risk of long-term complications.

Minimal radiation was also observed in internal organs such as the stomach and liver. At 8 weeks, the stomach received 0.06 mGy, while the liver received 0.01 mGy. No measurable radiation was detected in either organ at 15 weeks. These low doses are unlikely to have any significant impact on fetal organ development.

The digestive system, including the small intestine and colon, received approximately 0.02 mGy of radiation at 8 weeks. These low levels are generally considered safe and are unlikely to cause clinical concerns. Bone marrow, another radiation-sensitive tissue, received very low doses, with both active and shallow bone marrow exposed to 0.01 mGy at 8 weeks, posing minimal risk for conditions like bone marrow cancer or hematologic disorders.

The effective dose was also maintained at low levels, with an observed effective dose of 0.01 mSv. This is generally categorized as low risk, especially in the first trimester when critical neurological and physiological development occurs. These low radiation doses are considered safe, and the results suggest that the fetus was exposed to minimal radiation during the scans.

Organs such as the thyroid, spinal cord, digestive system, and bone marrow received doses ranging from 0.01 to 0.05 mGy. Although these doses do not pose significant clinical risk, it is essential to monitor every dose applied to developing fetal tissues. Overall, the radiation doses during these head CT scans were extremely low, with minimal risk of long-term effects on fetal development. However, due to the fetus's heightened sensitivity to radiation in early development, the use of low-dose protocols is strongly recommended. The effective dose of 0.01 mSv suggests low radiation exposure, with no significant impact on development expected. Nevertheless, alternative imaging modalities such as MRI or ultrasound should be considered whenever possible to further reduce radiation exposure.

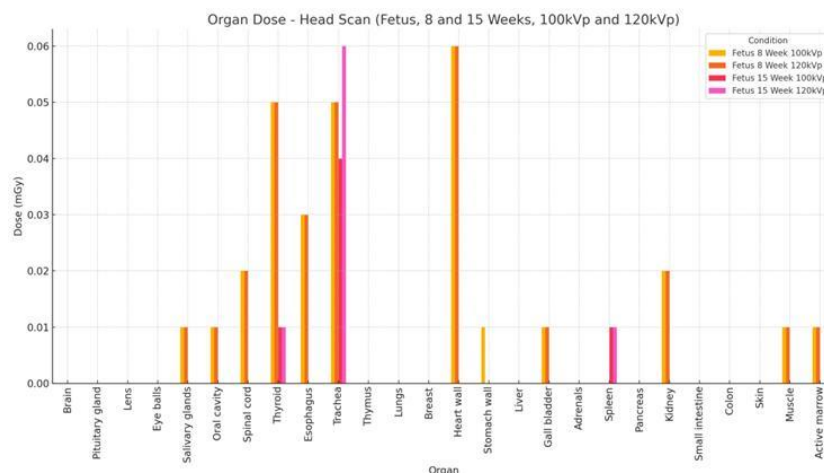


Figure 3: Fetus (8-15 Weeks) Phantom with Different kVp Organ Doses

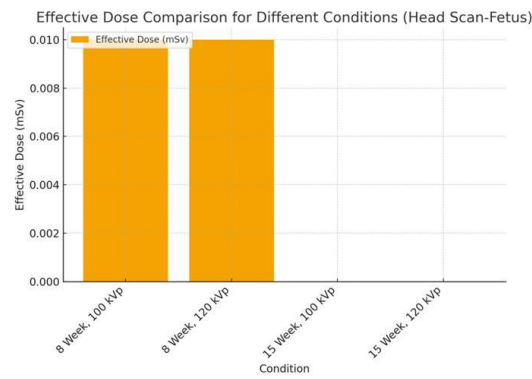


Figure 4: Fetus (8-15 Weeks) Phantom with Different kVp Effective Doses

The thoracic CT scan results performed at 8 and 15 weeks of gestation show varying radiation doses across different organs, emphasizing the importance of minimizing exposure, especially in radiation-sensitive organs.

Brain: The brain received relatively low doses during thoracic scans, ranging from 0.17 mGy to 0.2 mGy. While the brain is sensitive to radiation, these doses are low and pose no immediate clinical risk. However, the potential for cumulative radiation exposure and long-term neurological effects should not be overlooked, especially in individuals undergoing multiple scans.

Pituitary Gland: The pituitary gland, responsible for hormonal regulation, received doses between 0.19 mGy and 0.23 mGy. Though these levels are low, the gland's role in maintaining hormonal balance during pregnancy warrants careful monitoring. Even low doses could potentially impact long-term hormonal regulation, although no immediate harm is expected.

Eye Lenses and Eyeballs: The radiation doses observed for the eye lenses and eyeballs, ranging from 0.13 mGy to 0.17 mGy, are also low. The eye lens is highly sensitive to radiation, and while the risk of cataracts at these levels is minimal, the cumulative effects of repeated exposure should be considered. Currently, these doses are unlikely to cause significant clinical effects.

Salivary Glands: The salivary glands received higher radiation doses compared to other organs, with doses ranging from 1.34 mGy to 1.43 mGy. Long-term effects like salivary gland dysfunction or dry mouth may occur with repeated exposure. However, these doses are tolerable for single exams, although future scans should aim to reduce exposure to these glands.

Spinal Cord: The spinal cord received doses ranging from 6.31 mGy to 6.94 mGy. While these doses are not immediately harmful, the risk of nerve damage and neurological complications increases with cumulative exposure. Lower-dose protocols should be prioritized when scanning areas that expose the spinal cord, especially in pregnant patients.

Thyroid: The thyroid, highly sensitive to radiation, received significant doses of 17.22 mGy to 17.56 mGy. These levels could increase the long-term risk of thyroid cancer due to the thyroid's high radiation sensitivity. Shielding or minimizing exposure to the thyroid is highly recommended.

Esophagus and Trachea: These organs received radiation doses between 9.46 mGy and 11.00 mGy. While these doses are within acceptable limits, they may slightly increase the long-term risk of esophageal cancer. Immediate risks remain low, but cumulative exposure could have implications.

Lungs: The lungs, critical in radiation exposure, received doses ranging from 10.52 mGy to 11.27 mGy. This may increase the long-term risk of lung cancer, particularly with repeated exposure.

Reducing radiation to the lungs should be prioritized, especially for patients with pre-existing conditions or other risk factors like smoking.

Heart and Liver: The heart wall and liver received doses ranging from 8.89 mGy to 11.06 mGy. These organs could face long-term risks from cumulative radiation exposure, particularly for patients with pre-existing conditions. Repeated exposure to these doses may worsen underlying health issues.

Effective Dose: The overall effective dose ranged from 6.07 mSv to 6.48 mSv. While within acceptable limits for medical imaging, it is important to consider that the scan was performed on a pregnant patient. Lower-dose protocols should be used to minimize risks to the fetus.

Organ Doses: Radiation-sensitive organs like the thyroid, spinal cord, and lungs received moderate to high doses, especially at 120 kVp. The thyroid, in particular, is at higher risk due to its radiation sensitivity. Protective measures should be considered for future scans.

Fetal Risks: Although the thoracic scan was performed on the mother, minimizing fetal radiation exposure is essential. The effective doses fall within safe limits, but radiation exposure should always be minimized during pregnancy. Shielding and low-dose protocols are critical to protect both mother and fetus.

Comparison of Tube Voltages: Scans using 120 kVp resulted in higher radiation doses compared to 100 kVp. Whenever possible, lower-voltage scans (100 kVp) should be preferred to reduce radiation exposure without compromising diagnostic quality.

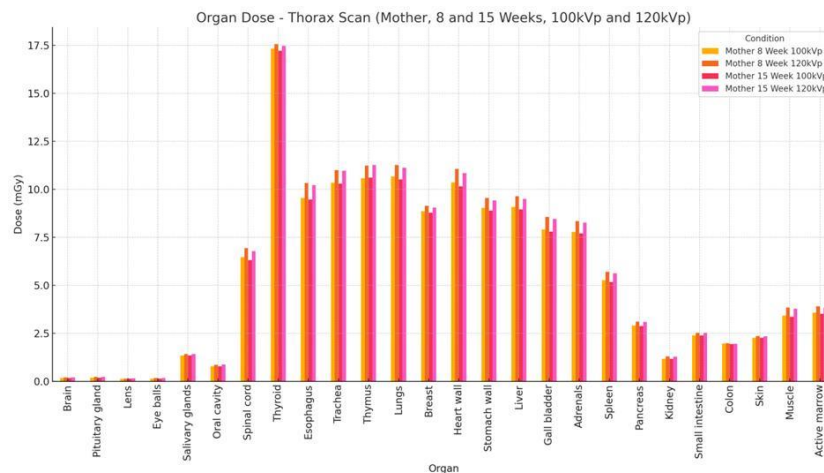


Figure 5: Mother Gestational Age (8-15 Weeks) Phantom with Different kVp Organ Doses

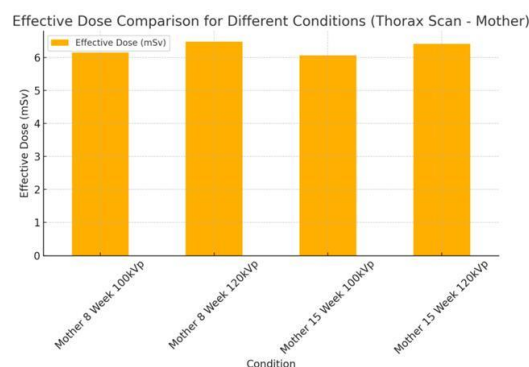


Figure 6: Mother Gestational Age (8-15 Weeks) Phantom with Different kVp Effective Doses

The fetal thoracic CT scan results at 8 and 15 weeks of gestation show minimal radiation exposure across most organs. Below is a detailed analysis of organ-specific radiation doses and their potential clinical impact on fetal development.

Brain and Pituitary Gland: At 8 weeks, no radiation exposure was detected in the brain and pituitary gland. However, at 15 weeks, these organs received doses between 0.05 mGy and 0.06 mGy. While these doses are low and unlikely to significantly affect fetal brain development, both the brain and the pituitary gland are highly sensitive to radiation. Therefore, even low-level exposure should be closely monitored to mitigate any potential risks to neurological development.

Eye Lenses and Eyeballs: No radiation was detected in the eye lenses and eyeballs at 8 weeks, but very low doses were recorded at 15 weeks (0.06–0.07 mGy). These doses pose minimal risk to eye health and are unlikely to cause cataracts. However, since fetal eye tissues are highly sensitive to radiation, continued monitoring is recommended to ensure no long-term adverse effects occur.

Salivary Glands and Oral Cavity: At 15 weeks, the salivary glands and oral cavity received low doses of radiation (0.04–0.05 mGy). While these doses are low and pose no significant risk to fetal development, the long-term effects on tissue development should be carefully evaluated, particularly with repeated exposure.

Spinal Cord: The spinal cord, crucial for fetal development, was exposed to doses between 0.04 and 0.06 mGy at 15 weeks. Although these levels do not pose substantial risks to spinal cord development, careful monitoring is recommended to protect this essential structure during critical periods of fetal growth.

Thyroid: The fetal thyroid, highly sensitive to radiation, received low doses (0.01 mGy at 8 weeks and 0.04–0.06 mGy at 15 weeks). While these doses are low and pose minimal risk, limiting radiation exposure to the thyroid is crucial. Monitoring and, where possible, shielding are advised to minimize exposure.

Lungs, Heart, and Chest Region: The fetal lungs, heart wall, and chest region were exposed to low doses (0.05–0.06 mGy) at 15 weeks. While these doses are low-risk for fetal development, the long-term effects on lung and cardiac function should be carefully monitored, especially given cumulative exposure.

Internal Organs (Stomach, Liver, Gallbladder, Kidneys): At 8 weeks, no radiation was detected in most internal organs, while at 15 weeks, doses ranged from 0.05 mGy to 0.09 mGy. These doses are low and generally pose no significant risks to fetal development. However, the long-term effects on organ growth and function should be considered, particularly with repeated imaging.

Digestive System (Small Intestine, Rectosigmoid Region): Radiation exposure to the small intestine and rectosigmoid region at 15 weeks ranged from 0.07 to 0.1 mGy. These doses are unlikely to impact fetal digestive system development, but minimizing exposure is recommended to reduce potential long-term risks.

Urinary and Reproductive Systems (Prostate, Testes, Ovaries): At 15 weeks, the bladder, prostate, testes, and ovaries were exposed to low doses (0.05–0.1 mGy). These doses are not expected to impact fetal reproductive system development significantly. However, since these organs are sensitive to radiation, close monitoring and dose minimization are advised.

Bone Marrow: Bone marrow, crucial for hematopoietic system development, received doses between 0.1 mGy and 0.12 mGy at 15 weeks. While these levels pose minimal risks to bone marrow

development, any radiation exposure to such sensitive tissues should be approached cautiously. The cumulative effects on long-term hematologic health warrant attention.

Effective Dose: The effective dose to the fetus at 15 weeks ranged from 0.07 to 0.09 mSv. These levels are within safe limits for fetal development. However, minimizing radiation exposure is essential due to the fetus's high sensitivity during early development. Lower-dose imaging protocols and alternative modalities, such as MRI or ultrasound, should be considered whenever feasible to avoid unnecessary radiation.

Although the radiation doses observed across fetal organs during thoracic scans are minimal, continued monitoring is vital to ensure long-term development is not adversely affected. This is particularly true for sensitive organs such as the brain, thyroid, spinal cord, and bone marrow. For organs like the thyroid and reproductive system, reducing exposure with dose minimization strategies and considering alternative imaging methods is highly recommended. The effective dose at 15 weeks remains within safe limits, but ongoing efforts to reduce fetal radiation exposure should be a priority, especially when repeated imaging is necessary.

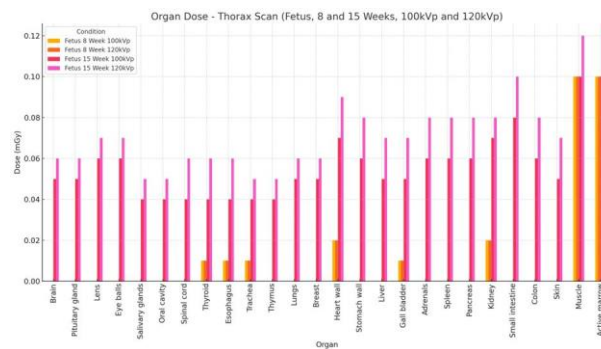


Figure 7: Fetus (8-15 Weeks) Phantom with Different kVp Organ Doses

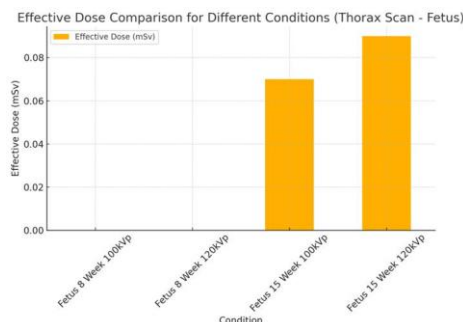


Figure 8: Fetus (8-15 Weeks) Phantom with Different kVp Effective Doses

DISCUSSION and CONCLUSION

This study used the NCICT dosimetric simulation tool, a Monte Carlo-based method, to estimate organ doses in pregnant individuals and fetuses from CT scans accurately (8,11). NCICT is a system that simulates radiation exposure to organs and calculates the effective dose during CT examinations (5). This tool was optimized in this study to improve performance in assessing organ doses for pregnant women and fetuses (4). The high-resolution simulation of radiation distribution within the body allows for precise dose estimation, crucial for reducing fetal exposure (2,10).

Patient-specific data were used to measure radiation doses in both pregnant patients and fetuses (5). Anthropomorphic models representing different stages of pregnancy (8 to 15 weeks) were utilized (3). Each model reflected the anatomical changes that occur during pregnancy and was

adapted for use with the NCICT system (6). These models were sourced from a comprehensive NCICT database, ensuring the accuracy and applicability of simulation outcomes in real clinical scenarios (8,11).

Organ dose calculations were performed using Monte Carlo simulations integrated into the NCICT system (7). The Monte Carlo method simulates radiation interactions with patient tissues in detail, enabling an accurate analysis of radiation deposition in specific organs (8). The simulations were integrated with the Python-based backend of the NCICT system for efficient processing, allowing scalability across multiple patient models and scan protocols (6,12).

For each CT examination (Table 1), patient-specific anatomical information and scan protocols were used to calculate organ doses. Custom Python scripts were created to optimize these calculations, ensuring the simulations were tailored to reflect individual patient characteristics, such as body size, organ positioning, and gestational stage—key factors for accurate dose estimation (3,13). The following steps were implemented:

1. **CT Scan Parameters:** A Python-based interface was developed to input CT scan parameters (kVp, mAs, scan length, spiral mode, etc.) for each patient. These parameters were selected based on clinical scan protocols typically used in pregnant patients undergoing diagnostic CT scans (6).
2. **Selection of Patient Models:** Anthropomorphic models for different gestational stages were used to simulate the anatomy of pregnant patients and fetuses. The model was selected from the NCICT database using a Python function, with each model tailored to accurately represent the anatomical changes at each gestational age (8).
3. **Monte Carlo Simulations:** Photon simulations were performed based on absorption coefficients assigned to each organ in the scanned region. Detailed calculations of energy transfer and radiation deposition were made, focusing on radiosensitive areas like the uterus and fetal organs (4,16).
4. **Calculation of Organ Doses:** Absorption values for each organ were converted into doses measured in milligrays (mGy). These doses were evaluated according to national and international radiation safety standards, including recommendations from the International Commission on Radiological Protection (ICRP) and the American Association of Physicists in Medicine (AAPM) (9,17).

Radiation dose calculations were performed using Monte Carlo simulation techniques integrated with the NCICT algorithm, following AAPM guidelines (9). The simulation results were validated against clinical CT Dose Index (CTDI) measurements (4). Additionally, comparisons with previously established dosimetric data in the literature further verified the accuracy of the calculated doses. This method is one of the most reliable for clinical dose assessment and is expected to guide future studies (8). Validation confirmed that simulated doses were within acceptable margins of error, demonstrating that the Monte Carlo method provides a robust framework for assessing fetal and maternal radiation exposure during CT scans (6). When CT scans are necessary during pregnancy, fetal protection measures should be implemented in addition to low-dose protocols. This recommendation may enhance the practical relevance of the study. These results highlight the importance of implementing low-dose protocols in clinical settings, which would strengthen the clinical impact of the study.

Future Applicability: This methodology can be applied in various clinical settings, allowing healthcare professionals to estimate radiation exposure more accurately and adjust CT scan protocols to minimize risk. As the NCICT system evolves, it could become a foundational tool for real-time dose optimization in clinical environments (8,19).

REFERENCES

1. Lazarus E, DeMasi R, Fisher E, Jain A, Kaewlai R. Computed tomography in pregnancy: evaluating radiation dose and risk. *J Am Coll Radiol*. 2009;6(4):228-33.
2. Miglioretti DL, Smith-Bindman R, Abraham L, et al. Radiology use in pregnant women and potential fetal doses. *Radiology*. 2011;259(3):773-81.
3. Wagner LK, Eifel PJ, Geise RA. Potential biological effects following high doses of diagnostic ultrasound: should we worry? *Radiology*. 1997;204(2):329-31.
4. Mettler FA Jr, Bhargavan M, Faulkner K, et al. Radiologic and nuclear medicine studies in the United States and worldwide: frequency, radiation dose, and comparison with other radiation sources—1950-2007. *Radiology*. 2008;253(2):520-31.
5. Goldberg-Stein S, Liu B, Hahn PF, Lee SI. Radiation dose management: part 2, estimating fetal radiation risk from CT during pregnancy. *AJR Am J Roentgenol*. 2011;196(4):805-11.
6. Angel E, Wellnitz CV, Yoshizumi TT, et al. Radiation dose to the fetus for pregnant patients undergoing multidetector CT imaging: Monte Carlo simulations estimating fetal dose for a range of gestational age and patient size. *Radiology*. 2008;249(1):220-7.
7. Xie T, Liu Q, Zhou Z, et al. Estimation of fetal dose for radiography exams during pregnancy: a comparison of methodologies. *Phys Med Biol*. 2018;63(18):185007.
8. Xu XG, Bednarz B, Paganetti H. A review of dosimetry studies on external-beam radiation treatment with respect to second cancer induction. *Phys Med Biol*. 2014;59(3).
9. ICRP. Recommendations of the International Commission on Radiological Protection. ICRP publication 103. Ann ICRP. 2007.
10. Brent RL. The effects of embryonic and fetal exposure to X-ray, microwaves, and ultrasound. *Pediatrics*. 1989;104:111-21.
11. McCollough CH, Schueler BA, Atwell TD, et al. Radiation exposure and pregnancy: when should we be concerned? *Radiographics*. 2007;27(4):909-17.
12. Stabin MG, Watson EE. Radiation dose to the embryo/fetus from radiopharmaceuticals. *Health Phys*. 1999;77(3):316-9.
13. Kuo LC, Wu RT, Wang SJ, et al. Fetal radiation exposure in pregnant women undergoing computed tomography scans: estimations from dose measurements in a simulated human abdomen. *AJR Am J Roentgenol*. 2011;197:658-62.
14. Hall EJ, Brenner DJ. Cancer risks from diagnostic radiology: the impact of new epidemiological data. *Br J Radiol*. 2012;85.
15. Parker MS, Hui FK, Camacho MA, et al. Female patients, pregnancy, and radiation exposure: what to expect. *Radiographics*. 2008;28(3):1083-9.
16. Scheuerlein C, Köhler S, Gabler S, et al. Dose optimization in radiography of pregnant patients using Monte Carlo simulations: effects on fetal dose. *Eur Radiol*. 2020;30(4):2145-51.
17. Nickoloff EL, Alderson PO. Radiation risk assessment in pregnant women undergoing imaging procedures: clinical recommendations. *Semin Ultrasound CT MR*. 2017;38(5):453-60.
18. Preston DL, Pierce DA, Shimizu Y, et al. Radiation effects on mortality from breast cancer among atomic bomb survivors. *Radiat Res*. 2002;158(3):198-209.
19. Boice JD Jr, Miller RW. Childhood and adult cancer after intrauterine exposure to ionizing radiation. *Teratology*. 1999;59(4):227-33.