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When Pregnancy Meets Nuclear Medicine: Diagnostic Challenges and Safety Protocols

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Abstract. Nuclear medicine plays a critical role in diagnosing and managing various medical conditions by using radiopharmaceuticals for functional imaging. While these procedures are generally safe for the general population, using them during pregnancy presents unique clinical challenges. The physiological changes that occur during pregnancy can alter the pharmacokinetics of radiotracers, which complicates image interpretation and dose estimation. Additionally, the potential for ionizing radiation to affect fetal development raises serious ethical and medical concerns. To systematically examine the diagnostic challenges and safety considerations associated with the use of nuclear medicine during pregnancy, this article conducts a narrative review of peer-reviewed literature, clinical guidelines, and expert consensus protocols. A qualitative narrative review approach was employed using medical databases such as PubMed, SciSpace, and Google Scholar. Relevant studies were identified using the following terms: "nuclear medicine," "pregnancy," "radiological safety," "radiopharmaceuticals," and "fetal exposure." Current evidence suggests that most nuclear medicine diagnostic procedures result in fetal doses below 20 mSv, which is below the threshold associated with deterministic effects. The safe practice of nuclear medicine during pregnancy requires striking a careful balance between the clinical needs of the mother and the protection of the fetus. This requires adhering to the ALARA principle and using modern dosimetry methods.

Highlights

1. Most diagnostic nuclear medicine procedures during pregnancy deliver fetal doses below thresholds associated with deterministic effects.

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2. Physiological changes in pregnancy significantly alter radiopharmaceutical pharmacokinetics, complicating image interpretation and fetal dose estimation.
3. Strict justification, ALARA-based optimization, and multidisciplinary protocols enable safe nuclear medicine use while protecting fetal development.

Keywords: Nuclear medicine, pregnancy, radiation safety, radiopharmaceuticals, safety protocols.

1. Introduction

Nuclear medicine has revolutionized the diagnosis and treatment of numerous pathologies by using radiopharmaceuticals to evaluate physiological and metabolic processes in vivo. This medical specialist employs small quantities of radioactive substances for diagnosing and treating diseases, offering distinctive functional insights that supplement conventional anatomical imaging techniques [1].

However, when a pregnant patient requires a nuclear medicine procedure, a complex clinical dilemma arises concerning the risk-benefit assessment for the mother and the developing fetus. Since the discovery of the biological effects of radiation, exposure to ionizing radiation during pregnancy has been a medical concern, particularly following epidemiological studies conducted on populations exposed to radiation, such as those in Hiroshima and Nagasaki [2].

Physiological changes during pregnancy can significantly alter the pharmacokinetics and biodistribution of radiopharmaceuticals. Increased blood volume, altered renal and hepatic function, and changes in body composition can affect the distribution of radiopharmaceuticals and the radiation dose received by maternal and fetal organs [3].

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The complexity of the issue is exacerbated by the limited availability of specific data on the effects of different radiopharmaceuticals during the various stages of pregnancy. Although international organizations, such as the International Commission on Radiological Protection (ICRP) and the Society of Nuclear Medicine and Molecular Imaging (SNMMI), have established general guidelines, the practical implementation of these protocols varies considerably between institutions and geographical regions [4] .

This article aims to provide a comprehensive review of the diagnostic challenges and safety protocols associated with nuclear medicine during pregnancy. This review is based on the latest scientific evidence and recommendations from specialized international bodies.

2. Theoretical Framework:

2.1 Fundamentals of Nuclear Medicine:

Nuclear medicine is based on the principle of using radiopharmaceuticals, which are radioisotopes bound to biologically active molecules that circulate throughout the body according to specific physiological processes. Unlike other imaging techniques, which mainly provide anatomical information, nuclear medicine offers functional and molecular information. This allows for the early detection of pathological processes before structural changes become apparent [5].

The most commonly used radiopharmaceuticals include:

- Technetium-99m (^{99}Tc): The most widely used radioisotope in diagnostic nuclear medicine. It has a half-life of six hours and emits gamma rays at 140 keV, making it ideal for imaging.
- Fluorine-18 (^{18}F): It is mainly used in positron emission tomography (PET) and has a half-life of 110 minutes.
- Iodine-131 (^{131}I): It is used for the diagnosis and treatment of thyroid diseases and has a half-life of eight days.
- Gallium-67 (^{67}Ga): Used to detect infections and inflammation.

2.2 Physiological Changes During Pregnancy:

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The pharmacokinetics of radiopharmaceuticals may be significantly affected by the different physiological alterations that pregnancy brings about.

Cardiovascular changes: During pregnancy, cardiac output may increase by as much as 50%, while blood volume increases by 40% to 50%. Together, these modifications and a decrease in peripheral vascular resistance influence how radiopharmaceuticals are distributed throughout the mother's circulation.

Renal change: There are significant changes to the renal system, such as an increase in renal blood flow and a 50% glomerular filtration rate. Furthermore, changes in tubular reabsorption may impact radiopharmaceutical excretion, impacting exposure for both the mother and the fetus.

Hepatic change: Due to changes in plasma protein synthesis, metabolizing enzyme activity, and hepatic blood flow, pregnancy also has an impact on hepatic function. The metabolism and excretion of radiopharmaceuticals may be affected by these hepatic changes.

Hepatic change: Pregnancy also affects hepatic function because of modifications in metabolizing enzyme activity, hepatic blood flow, and plasma protein production. These hepatic alterations may impact radiopharmaceutical metabolism and excretion.

2.3 Embryonic and Fetal Development:\

Assessing the possible dangers of radiation exposure at different stages of pregnancy requires an understanding of embryonic and fetal development.

1. Pre-implantation period (0–2 weeks): The embryo is extremely vulnerable to fatal consequences during this early phase. The "all-or-nothing" outcome, in which the embryo either survives without deformities or does not, can occur from any considerable radiation exposure. In general, there is little chance of abnormalities during this time.

2. The organogenesis period (2–8 weeks): During this time, the primary organs are developing, making it the most vulnerable to abnormalities. It is a time when teratogenic effects are most

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likely to occur, which means that exposure to dangerous substances, such as radiation, might result in serious structural defects.

3. Fetal period (8–40 weeks): Organs continue to grow and develop during this time. Radiation exposure can endanger growth and neurobehavioral development, which may result in long-term functional impairments, and the central nervous system is particularly sensitive.

3. Methodology

In order to investigate the safety procedures and diagnostic difficulties related to nuclear medicine during pregnancy, this study used a qualitative narrative review methodology. Several reputable scientific databases were used in a methodical literature search to guarantee thorough coverage of pertinent studies.

3.1 Research Strategy

To find relevant material, a thorough search was done across multiple important databases. These included Google Scholar, a multidisciplinary academic search engine; SciSpace, an academic search platform that offers full-text access; PubMed/MEDLINE, which is acknowledged as the main database of medical literature; and Scopus, which offers comprehensive coverage of citations and abstracts of scientific literature.

3.2 Search Terms

Both primary and secondary search phrases were used in the literature search. "Nuclear medicine," "pregnancy," "radiation safety," "radiopharmaceuticals," and "fetal exposure" were among the key terms. The search was further narrowed down by using secondary phrases such as "diagnostic imaging," "ICRP guidelines," "SNMMI protocols," "Dosimetry," and "Risk assessment."

3.3 Inclusion and Exclusion Criteria

The inclusion criteria for the review encompassed articles published between 2015 and 2025, including original research, systematic reviews, and clinical guidelines. Only studies focusing on

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nuclear medicine during pregnancy and demonstrating direct clinical relevance were considered. The exclusion criteria eliminated articles published before 2015, unless they provided important historical context, studies conducted exclusively in animals without clinical applicability, isolated clinical cases lacking generalizability, and articles for which abstracts or full texts were inaccessible.

3.4 Study Selection and Analysis

The initial search identified 240 potentially relevant articles. After removing duplicates and applying the defined inclusion and exclusion criteria, 89 studies were selected for a more detailed analysis. The data were examined thematically to identify prevalent diagnostic challenges, current safety protocols, dosimetric estimation methods, evidence-based recommendations, and areas that require further research.

4. Results and Discussion

4.1 Diagnostic Challenges in Nuclear Medicine During Pregnancy

4.1.1 Pregnancy Detection

One of the most fundamental challenges in nuclear medicine is detecting pregnancy on time before administering radiopharmaceuticals. Evidence suggests that a significant percentage of pregnancies go unrecognized during the first few weeks, when nuclear medicine studies may be performed [4].

Table 1: *Recommended Detection Protocol*

Age Group	Action Required	Justification
Women under 12 years	No test required	Prepubescent

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Women 12-55 years	Questionnaire + test if indicated	Reproductive age
Women over 55 years	Questionnaire only	Probably postmenopausal
History of hysterectomy	Document in medical history	Pregnancy impossible

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The standard questionnaire should include the following:

- Date of last menstrual period
- Use of contraceptive methods
- Recent sexual activity
- Symptoms of pregnancy
- History of infertility or menopause

4.1.2 Changes in Image Interpretation

The physiological changes that occur during pregnancy can significantly alter the normal biodistribution of radiopharmaceuticals, creating unique challenges in interpretation.

Changes in bone scintigraphy:

- Increased uptake in the sacroiliac joints
- Increased activity in the pubic symphysis
- Possible uptake in the ribs due to chest expansion

Changes in Pulmonary Perfusion:

- Alterations in pulmonary vascular distribution

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- Changes in the ventilation/perfusion ratio
- Possible compression of the inferior vena cava

Alterations in renal studies:

- Increase in glomerular filtration rate
- Changes in radiopharmaceutical clearance
- Possible physiological hydronephrosis

4.1.3 Multidisciplinary Coordination

Due to the complex nature of nuclear medicine during pregnancy, close coordination between multiple specialties is required.

Required Multidisciplinary Team: Nuclear physician, Obstetrician/gynecologist, Medical physicist, Radiation protection officer, Nuclear medicine technologist, and Maternal-fetal medicine specialist [7].

4.2 Radiological Safety Protocols

4.2.1 Fundamental Principles

The safety protocols for nuclear medicine during pregnancy are based on three fundamental principles established by the ICRP.

1. Justification: Each procedure must be medically justified, ensuring that the benefits to maternal health outweigh the potential risks to the fetus
2. Optimization (ALARA principle): Doses should be kept "as low as reasonably achievable," taking into account economic and social factors
3. Dose Limitation: Although there are no specific dose limits for pregnant patients, reference levels should be considered to guide clinical practice.

4.2.2 Current International Guidelines

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Current international guidelines emphasize careful management of radiation exposure during pregnancy, with the ICRP 103 recommendations stating that a fetal dose of less than 100 mGy carries negligible deterministic risk, while doses above 100 mGy require case-by-case assessment, and termination of pregnancy should only be considered for exposures greater than 500 mGy. The SNMMI protocols highlight the importance of using diagnostic reference levels, optimizing imaging protocols, documenting clinical justifications thoroughly, and providing both pre- and post-procedure counseling. Similarly, the EANM guidelines stress prioritizing non-ionizing modalities when possible, applying specific protocols tailored to different radiopharmaceuticals, and giving special attention to breastfeeding considerations.

4.2.3 Practical Implementation of Protocols

Effective implementation of safety protocols necessitates both clear institutional policies and comprehensive staff training. Standardised pregnancy detection methods, informed consent guidelines, a well-defined chain of accountability, established emergency protocols for unintentional exposures, and comprehensive post-procedure documentation with suitable follow-up are all examples of institutional measures. Continuous staff training, which includes regular updates on safety procedures, regular emergency exercises, keeping abreast of international rules, and guaranteeing proficiency in crucial dosimetric calculations, is equally crucial. When combined, these components form a well-organized framework that protects patients and healthcare professionals while encouraging adherence to best practices [8].

4.3 Risks of Fetal Exposure and Safety Thresholds

4.3.1 Classification of Radiobiological Effects

Deterministic and stochastic radiobiological effects are the two main categories into which the dangers of fetal exposure to ionizing radiation are typically divided. Once a threshold dose is reached, deterministic effects include mental impairment, intrauterine growth restriction, congenital abnormalities, and embryonic or fetal mortality. On the other hand, stochastic

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effects—which mostly involve an elevated risk of carcinogenesis and hereditary genetic effects—do not have a clear threshold and can happen even at lower dosages.

4.3.2 Dose Thresholds and Associated Risks

Table 2: *The following table summarizes the dose thresholds and associated risks according to current scientific evidence*

Fetal Dose (mGy)	Potential Effects	Critical Period	Clinical recommendation
< 50	Negligible Risk	All periods	Justified procedure
50-100	Minimal Deterministic Risk	Organogenesis	Careful assessment
100-200	Possible Minor Effects	8-15 weeks	Specialist consultation
200-500	Moderate Risk	8-25 weeks	Multidisciplinary assessment
> 500	Significant Risk	All periods	Consider termination

4.3.3 Typical Doses in Nuclear Medicine Procedures

Table 3: *Common Diagnostic Procedures*

Procedure	Radiopharmaceuticals	Typical Activity (MBq)	Estimated Fetal Dose (mGy)
Bone scan	^{99}Tc-MDP	740-925	4.0-6.0
Pulmonary perfusion scan	^{99}Tc-MAA	185-370	0.6-1.2
Renal scan	^{99}Tc-DTPA	370-555	1.5-2.5
FDG-PET scan	^{18}F-FDG	370-555	7.0-10.0
Thyroid scan	^{99}Tc-pertechnetate	185-370	1.1-2.2

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Note: Fetal doses are estimates based on dosimetric models and may vary depending on gestational age and maternal characteristics.

4.4 Pharmacokinetics of Radiopharmaceuticals During Pregnancy

The distribution, metabolism, and excretion of radiopharmaceuticals are all impacted by the physiological changes that take place during pregnancy. Increased distribution volume, which comprises a 40%–50% increase in plasma volume, an increase in total body water, and a decrease in plasma protein content, is the main factor causing changes in biodistribution. Metabolic alterations are also important; variations in hepatic blood flow, hepatic enzyme activity, and conjugation and excretion processes affect how radiopharmaceuticals behave. The clearance and bioavailability of radiopharmaceuticals can also be altered by renal changes, such as a 50% increase in glomerular filtration rate, an increase in renal blood flow, and modifications in tubular reabsorption.

A number of variables, including molecular weight, fat solubility, degree of ionization, plasma protein binding, and the existence of certain transporters, affect how well radiopharmaceuticals pass across the placental barrier. Radioactive iodine isotopes (^{131}I, ^{123}I), gallium-67, and thallium-201 are examples of radiopharmaceuticals with strong placental transfer, while technetium-99m chelates (DTPA, DMSA) and ^{99}mTc-labeled albumin macroaggregates are examples of those with limited placental transfer. Because of these differences, fetal exposure must be carefully considered, especially if the radiopharmaceutical may concentrate in developing tissues.

Special considerations are required for each trimester. The first trimester (0–12 weeks) represents the period of maximum teratogenic sensitivity, coinciding with the development of major organs, necessitating extreme caution with radiopharmaceuticals. The second trimester (13–27 weeks) is generally considered the safest period for necessary procedures, although the central nervous system continues developing and fetal growth accelerates. During the third trimester (28–40 weeks), maturation of fetal organs occurs, and logistical considerations arise

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due to increased uterine size, with preparation for delivery and breastfeeding influencing procedural decisions [9].

4.5 Dosimetric Estimation Methods

Accurate estimation of fetal dose is essential for assessing risks associated with radiopharmaceutical exposure. Current dosimetric models include gestational phantom models, such as mathematical phantoms of pregnant women, high-resolution voxelized models, and Monte Carlo simulations for radiation transport. Fetal dose coefficients, expressed in mGy per MBq administered, vary according to gestational age, the specific radiopharmaceutical used, and maternal biodistribution.

Multiple factors affect fetal dosimetry. Maternal variables include body weight and composition, renal and hepatic function, gastrointestinal transit time, and hydration status. Radiopharmaceutical variables encompass the physical properties of the radioisotope, biological characteristics of the drug, route of administration, and administered activity. Gestational variables, such as fetal size and position, amniotic fluid volume, and uterine wall thickness, also influence dose estimates. Despite these models, limitations persist, including individual variability in maternal pharmacokinetics, variations in gestational anatomy, and genetic factors affecting metabolism. Models are often based on average anatomy, fail to account for maternal or fetal pathologies, and assume standard biodistribution. Additionally, uncertainties arise due to limited human studies, extrapolation from animal data, and measurement variability [10].

4.6 Specific Clinical Cases and Recommendations

Pulmonary thromboembolism (PTE) is a serious complication in pregnancy, with an incidence of 1–2 cases per 1,000 pregnancies. Diagnosis is challenging because nonspecific symptoms often overlap with normal pregnancy changes, laboratory tests such as D-dimer are physiologically elevated, and concerns exist regarding fetal radiation exposure. Recommended protocols involve an initial clinical evaluation and assessment of pre-test probability, followed by Doppler ultrasound of the lower extremities. If results are negative but clinical suspicion remains high,

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first-trimester patients may undergo perfusion scintigraphy, while second- and third-trimester patients may require pulmonary CT angiography or V/Q scintigraphy. Multidisciplinary risk–benefit assessment is essential. Dosimetric considerations indicate that fetal doses from perfusion scintigraphy, CTPA, and V/Q scintigraphy range from approximately 0.24–1.4 mGy.

Hyperthyroidism affects roughly 0.2% of pregnancies and poses risks to both mother and fetus. Radioactive iodine is contraindicated, while thyroid scintigraphy with ^{99}mTc may be considered only in select cases. Non-ionizing methods, including ultrasound and laboratory evaluation, are preferred. Management involves biochemical confirmation (TSH, free T4, T3), antibody assessment (TRAb, TPO), and thyroid ultrasound as the primary imaging tool. Scintigraphy with ^{99}mTc is reserved for situations where it is necessary for clinical management.

Detection of infectious or inflammatory foci may occasionally necessitate nuclear medicine during pregnancy. Potential indications include suspected osteomyelitis, fever of unknown origin, infectious endocarditis, or infected joint prostheses. Ultrasound is the preferred first-line diagnostic modality, with MRI without gadolinium or CT with fetal protection considered if necessary. When nuclear medicine cannot be avoided, bone scintigraphy using ^{99}mTc-MDP or leukocytes labeled with ^{99}mTc-HMPAO may be employed, but only with careful risk–benefit evaluation to minimize fetal exposure [11].

4.7 Non-Ionizing Diagnostic Alternatives

Non-ionizing imaging modalities provide valuable diagnostic alternatives during pregnancy, minimizing fetal exposure to radiation while allowing essential maternal and fetal assessment. Ultrasonography is widely considered the first-line imaging modality due to its safety, versatility, and accessibility. It offers several advantages, including the absence of ionizing radiation, real-time imaging capabilities, relatively low cost, and broad availability. Clinically, ultrasonography is used for maternal cardiovascular assessment, detection of deep vein thrombosis, evaluation of renal function, and imaging of the thyroid and other soft tissues. However, its utility can be limited by operator dependence, interference from intestinal gas or maternal obesity, restricted functional information, and unsuitability for certain indications.

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Magnetic resonance imaging (MRI) has been established as a safe imaging option during pregnancy, particularly after the first trimester. Studies have shown no evidence of adverse fetal effects, though gadolinium-based contrast agents should be avoided, and caution is advised during early pregnancy. MRI is useful in evaluating pulmonary embolism through MR angiography, maternal neurological conditions, abdominal masses, and musculoskeletal pathology. Pregnancy-specific protocols include using rapid sequences to minimize fetal movement, avoiding sequences with high specific absorption rates (SAR), ensuring comfortable patient positioning, and monitoring fetal well-being during longer procedures.

While computed tomography (CT) involves ionizing radiation, it may be necessary in urgent or life-threatening situations. Fetal protection strategies such as lead shielding of the abdomen, low-dose protocols, limiting the scan field, and using noise reduction techniques are essential to minimize exposure. Appropriate indications for CT include severe maternal trauma, suspected pulmonary embolism when ultrasound is inconclusive, acute intracranial pathology, and cases of appendicitis with inconclusive ultrasound findings. The advantages of a timely and precise maternal diagnosis in these situations typically exceed the possible dangers of fetal radiation exposure [12].

5. Specific Safety Protocols by Procedure

5.1 Bone Scan

One of the most often requested nuclear medicine procedures is a bone scan, which may be necessary during pregnancy to assess infection or bone metastases. It is crucial to verify pregnancy and ascertain gestational age before the procedure, evaluate the clinical rationale for the scan, take into account alternate imaging modalities like MRI or ultrasound, and get the patient's full informed permission. Safety precautions during the procedure include minimizing acquisition time, encouraging frequent bladder emptying, making sure you are properly hydrated to support renal elimination, and lowering the administered activity if at all possible without sacrificing diagnostic quality. Patients should be instructed to stay hydrated for the next 24 to 48 hours following the procedure, take contact precautions, and have the necessary

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clinical follow-up. Dosimetric estimation indicates that the typical administered activity ranges from 740 to 925 MBq of ^{99}Tc-MDP, with an estimated fetal dose of 4–6 mGy and an estimated maternal dose of 5–7 mSv [13].

5.2 Pulmonary Perfusion Studies

Because of the elevated risk of pulmonary thromboembolism during pregnancy, pulmonary perfusion tests are especially pertinent. Special concerns include lowering the quantity of macroaggregated albumin (MAA) particles to 50,000–100,000 instead of the typical 200,000–500,000, carefully monitoring maternal cardiopulmonary function, and doing breathing tests only when necessary. In order to prevent excessive microembolism, the pregnancy protocol has been modified to prioritize comfortable patient placement while avoiding prolonged supine posture, gradual injection, and obtaining the fewest projections required for diagnostic purposes. Interpretation of results must also account for the physiological changes that occur during pregnancy [13].

5.3 Renal Studies

Renal studies may be required during pregnancy to evaluate renal function, detect urinary obstruction, or investigate urinary tract infections. Preferred radiopharmaceuticals include ^{99}mTc-DTPA for glomerular filtration assessment, ^{99}mTc-MAG3 for evaluating tubular function, and ^{99}mTc-DMSA for detecting renal scarring, although the latter is rarely indicated during pregnancy. Safety protocols involve pre- and post-procedure hydration, frequent bladder emptying, lateral positioning to avoid vena cava compression, and careful monitoring of maternal vital signs throughout the study [13].

5.4 Positron Emission Tomography (PET)

FDG PET may be necessary during pregnancy for cancer staging or evaluation of infectious processes, though it involves relatively high radiation exposure compared to other nuclear medicine procedures. Special considerations include fasting prior to the procedure, especially in

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patients with gestational diabetes, prolonged acquisition time, and the potential need for sedation in cases of claustrophobia. The PET protocol in pregnancy requires thorough evaluation of clinical justification, mandatory multidisciplinary consultation, optimization of the FDG dose, and appropriate nutritional preparation before the procedure. During the scan, continuous monitoring of maternal well-being, comfortable positioning, minimized scan time, and adequate hydration are essential. Post-procedure, patients should receive radiological precaution instructions, undergo close clinical follow-up, and have detailed documentation of the administered dose [14].

6. Considerations for Breastfeeding

6.1 Transfer of Radiopharmaceuticals to Breast Milk

When considering breastfeeding in the context of nuclear medicine, it is important to understand the potential transfer of radiopharmaceuticals to breast milk. Most radiopharmaceuticals administered to the mother are excreted into breast milk to varying degrees, which can result in the infant being exposed to ionizing radiation. The extent of this excretion depends on several factors, including the physicochemical properties of the radiopharmaceutical, its binding affinity to milk proteins, the pH of the breast milk, and the physical and biological half-life of the radioisotope. These factors collectively influence how much of the radiopharmaceutical enters the milk and the duration of exposure, thereby guiding recommendations for breastfeeding interruption or modification following nuclear medicine procedures.

6.2 Recommendations by Radiopharmaceutical

Table 4: *Technetium-99m (half-life: 6 hours)*

Radiopharmaceutical	Downtime	Justification
^{99m}Tc-Pertechnetate	12–24 hours	High concentration in milk

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^{99m}Tc-MDP	6–12 hours	Rapid renal excretion
^{99m}Tc-MAA	6–12 hours	Low transfer
^{99m}Tc-DTPA	6 hours	Rapid renal elimination

Radioactive Iodine:

- ^{131}I is contraindicated during breastfeeding (permanent discontinuation).
- ^{123}I requires discontinuation for 2–3 weeks.

Fluorine-18 FDG:

- Discontinuation: Consider milk extraction and disposal.

6.3 Breastfeeding Management Protocol

Breastfeeding management in the context of radiopharmaceutical administration requires careful planning both before and after the procedure.

It is crucial to go over all of the alternatives with the patient before the treatment, including the decision to stop breastfeeding permanently or temporarily. In order for patients to retain their milk supply and securely store expressed milk in the event that a temporary cessation is selected, they should be educated on appropriate milk expression and storage practices. To ensure that the infant's nutritional needs are satisfied throughout the nursing break, preparation for alternate feeding techniques should also be considered.

Post-procedure, clear and specific instructions must be provided regarding the recommended duration of breastfeeding discontinuation. Safety verification methods, such as using a radiation monitor, are crucial to confirm that residual radioactivity in breast milk has decreased to safe levels. Proper extraction and disposal techniques

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should be followed to prevent unnecessary radiation exposure. Finally, monitoring the infant's well-being is important to ensure that any potential adverse effects from exposure are promptly identified and managed [15].

7. Ethical and Legal Considerations

7.1 Fundamental Ethical Principles

Pregnancy-related nuclear medicine poses difficult moral conundrums that call for thorough evaluation of several different concepts. Autonomy places a strong emphasis on the patient's entitlement to full knowledge, their capacity for decision-making, their respect for personal preferences, and their adherence to cultural and religious norms. Maximizing maternal benefit, taking into account the health of the fetus, evaluating both immediate and long-term advantages, and guaranteeing quality of life following the surgery are the main goals of beneficence. Minimizing possible harm by meticulous risk assessment, taking long-term impacts into account, and avoiding needless exposure are all important for non-maleficence. Fair access to required processes, equitable resource allocation, socioeconomic consideration, and nondiscrimination are all guaranteed by justice.

7.2 Informed Consent

Informed consent in nuclear medicine during pregnancy must be particularly thorough. The essential elements of consent include:

1. Procedure information: Patients should be made aware of the purpose of the study, the radiopharmaceutical that will be used, how long it will take, and any preparations that may be necessary.
2. Benefits and hazards: This entails outlining the anticipated diagnostic advantages, the predicted fetal risks, the risks to the mother, and the repercussions of not conducting the study.
3. Available alternatives – Alternatives include non-ionizing imaging modalities, conservative management options, alternative procedures, or delaying the study until after delivery.

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4. Dosimetric information – Patients should receive details on estimated fetal dose, comparison with natural exposures, relative risk context, and uncertainties in the dose estimates.
5. Follow-up and precautions – Clear post-procedure instructions should be provided, along with contact precautions, clinical follow-up guidance, and encouragement to reach out with any questions or concerns.

7.3 Legal Responsibilities

The legal responsibilities in nuclear medicine during pregnancy are distributed among healthcare providers and institutions. The nuclear physician is responsible for proper assessment of clinical justification, optimization of imaging protocols, detailed documentation of clinical decisions, and appropriate post-procedure follow-up. Institutions must maintain clear radiation protection policies, conduct regular staff training, provide adequate protective equipment, and implement quality and audit systems. Accurate dosimetric calculations, technical procedure optimization, radiation protection advice, and equipment and procedural safety verification are all under the purview of the medical physicist [15].

8. Technological Advances and Future Prospects

8.1 Developments in Fetal Dosimetry

The creation of sophisticated computer models, such as high-resolution voxelized phantoms and more precise Monte Carlo simulations, has fueled recent developments in prenatal dosimetry. The accuracy of fetal dosage estimates is increased by these models, which are increasingly customized to particular gestational ages and account for individual anatomical heterogeneity. New approaches, like image-based tailored dosimetry and the incorporation of individual biodistribution data, are emerging with advancements in computation. In an effort to provide more accurate and personalized evaluations of fetal radiation exposure, population pharmacokinetic models and artificial intelligence approaches are also being investigated for optimizing dosimetry estimates.

8.2 New Generation Radiopharmaceuticals

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New radiopharmaceuticals are being developed with an emphasis on features that improve diagnostic performance while lowering fetal danger. Reduced placental transfer, quicker elimination, improved diagnostic specificity, and a reduced total radiation dosage are all characteristics of ideal agents. Targeted nanoparticles, optimized theranostic agents, ultra-short half-life radioisotopes, and particular peptide-based radiopharmaceuticals are examples of recent advancements in this sector. These developments aim to preserve or increase imaging quality while improving safety profiles for expectant patients.

8.3 Hybrid Imaging Technologies

There is a great deal of promise for lowering fetal radiation exposure while enhancing diagnostic capabilities with hybrid imaging methods like PET/MRI and SPECT/MRI. By concurrently gathering functional and anatomical data, PET/MRI improves tissue characterization. Pregnancy-specific methods are adjusted for this process. Similar developments in SPECT/MRI include the creation of hybrid detectors, faster imaging procedures, less motion artifacts, and better temporal resolution. The safety and effectiveness of nuclear imaging in pregnant women are improved by these advancements taken together.

8.4 Artificial Intelligence and Machine Learning

In nuclear medicine, artificial intelligence (AI) and machine learning are being used more and more to enhance safety and customization. Personalized risk assessment, automatic pregnancy identification in imaging studies, individual biodistribution prediction, and automatic protocol optimization are some possible uses. These technologies are anticipated to provide significant advantages, such as decreased needless exposure, enhanced diagnostic precision, protocol customization, and automated dosimetric computations. Future developments in fetal imaging and patient-specific radiation management are probably going to heavily rely on these AI-driven technologies.

9. Evidence-Based Recommendations

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9.1 Clinical Decision Algorithm

A structured algorithm is suggested to direct decision-making in nuclear medicine during pregnancy based on the reviewed evidence. Pregnancy detection and confirmation is the first step. This include verifying the gestational age, conducting a pregnancy test where necessary, and employing a standard questionnaire for women of reproductive age. The assessment of clinical justification is the second phase. It is critical to ascertain whether the study can be delayed until after delivery, whether non-ionizing alternatives are available, whether it would impact clinical treatment, and whether it is medically necessary.

The evaluation of options is the third phase. Ultrasound, gadolinium-free magnetic resonance imaging, conservative treatment, or postponing the investigation until after delivery are among the options. The fourth phase is to guarantee safety and make an informed judgment if nuclear medicine is judged required. This entails gaining thorough informed consent, calculating the estimated fetal dose, consulting with other disciplines, and simplifying the study methodology.

The fifth step is procedure execution, which focuses on adhering to an optimal protocol to reduce procedure duration and dose, keeping a close eye on the mother's health during the process, keeping thorough records, and giving clear instructions after the treatment. In order to guarantee the safety of both the mother and the fetus, the last phase is follow-up, which entails obstetric follow-up, proper clinical evaluation, comprehensive documenting of outcomes, and continuous communication with the treating team.

9.2 Recommendation Levels

The level of evidence that is currently available determines the classification of recommendations. Pregnancy testing for women of reproductive age before nuclear medicine procedures, using ALARA principles in all procedures during pregnancy, prioritizing non-ionizing alternatives when appropriate, and obtaining detailed informed consent that includes fetal dose estimates are all examples of Level A (strong evidence) evidence. Level B (moderate evidence) includes multidisciplinary consultations for complex cases, standardizing institutional protocols

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for nuclear medicine during pregnancy, optimizing technical protocols to minimize fetal exposure, and using updated fetal dose coefficients for risk estimation. Considering pregnancy termination only for fetal doses greater than 500 mGy, taking special breastfeeding precautions depending on the radiopharmaceutical used, monitoring children exposed in utero for an extended period of time, and creating institution-specific protocols adapted to local resources are all included in Level C (limited evidence/expert opinion).

9.3 Quality Indicators

To ensure effective implementation of these protocols, several quality indicators are recommended. Process indicators include the percentage of women of reproductive age who receive a pregnancy questionnaire, the proportion of cases with documented multidisciplinary consultation, the frequency of use of non-ionizing alternatives when available, and the completeness of informed consent documentation. Outcome indicators encompass the incidence of unnoticed exposures during pregnancy, the accuracy of fetal dose estimates, patient satisfaction with the consent process, and adherence to institutional protocols. Safety indicators include the number of adverse events related to fetal exposure, the incidence of procedure-related maternal complications, the frequency of reviews of complex cases, and the response time for emergency consultations.

10. Limitations and Areas for Future Research

10.1 Limitations of Current Evidence

Current evidence in nuclear medicine during pregnancy is constrained by several methodological, data-related, and practical limitations. Methodologically, there is a lack of prospective controlled studies, significant variability in dosimetric methodologies, limited long-term follow-up, and heterogeneity in the populations studied. Data limitations further complicate interpretation, as many dosimetric estimates rely on theoretical models rather than direct measurement, individual pharmacokinetic variability is often unaccounted for, there is limited data on long-term effects, and uncertainties persist regarding risk coefficients. From a

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practical standpoint, variability in protocol implementation across institutions, differences in available resources, inconsistencies in staff training, and limitations in access to diagnostic alternatives all pose challenges to achieving consistent and reliable outcomes.

10.2 Priority Areas for Research

Several areas warrant focused research to address current knowledge gaps. In clinical research, prospective cohort studies of children exposed in utero are essential, along with assessments of long-term neurobehavioral effects, analyses of risk factors for adverse outcomes, and development of biomarkers for fetal exposure. Technological research priorities include developing radiopharmaceuticals with lower placental transfer, improving computational dosimetric models, optimizing hybrid imaging protocols, and implementing artificial intelligence to enhance dosimetry accuracy. Research on protocols should focus on comparing different optimization strategies, evaluating the effectiveness of training programs, conducting cost-effectiveness analyses of various approaches, and developing region- or country-specific guidelines to standardize practices.

10.3 Recommendations for Future Research

Recommendations for future research can be organized into short-, medium-, and long-term priorities. Short-term priorities (1–3 years) include establishing international fetal exposure registries, developing standardized informed consent protocols, implementing post-procedure follow-up systems, and creating updated dosimetry coefficient databases. Medium-term priorities (3–7 years) involve conducting multicenter long-term follow-up studies, developing personalized dosimetry models, evaluating new radiopharmaceuticals in gestational models, and implementing artificial intelligence technologies for dosimetry optimization. Long-term priorities (7–15 years) focus on analyzing transgenerational effects, advancing personalized nuclear medicine approaches for pregnancy, achieving full integration of hybrid imaging modalities, and establishing harmonized international regulatory frameworks to ensure safe and standardized practices globally.

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11. Conclusions

One of the greatest challenges facing modern healthcare is nuclear medicine during pregnancy. It necessitates carefully balancing the protection of the growing fetus with the mother's diagnostic requirements. Several important points that ought to direct clinical practice are revealed by this thorough analysis of the most recent scientific literature.

11.1 Synthesis of Main Findings

The majority of diagnostic nuclear medicine procedures, according to available data, produce fetal doses that are below the thresholds associated with notable deterministic consequences. The risk of congenital abnormalities or major developmental effects is extremely low at usual doses below 20 mSv for routine procedures, especially when contrasted with the baseline risk of 2–4% in the general population.

Clinical Justification: Each nuclear medicine procedure carried out during pregnancy needs to have a thorough justification. The immediate diagnostic benefit should be taken into account, but so should the implications for therapeutic management and long-term consequences for both the mother and the fetus. To make sure that only appropriate processes are carried out, multidisciplinary meetings and the employment of structured decision algorithms are necessary.

Recent developments in computationally dosimetry models, including advanced Monte Carlo simulations and high-resolution voxelized phantoms, have greatly increased the accuracy of fetal dosage estimates. Individual diversity in the pharmacokinetics and biodistribution of radiopharmaceuticals, however, remained largely unknown.

11.2 Implications for Clinical Practice

Standardized protocols must be developed and put into place by nuclear medical institutes. These protocols must contain explicit steps for determining fetal doses, evaluating clinical justifications, detecting pregnancies, and performing post-procedure follow-ups. Regular

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updates to these standards are necessary to take into account new scientific findings and suggestions from global organizations.

Continuous Staff Training: Because nuclear medicine during pregnancy is so complicated, all staff members engaged need to stay current on their knowledge of radiation protection, fetal dosimetry, and risk communication. Patient communication, ethical issues, and technological concerns should all be covered in training programs.

Creation of Collaborative Networks: Because these circumstances are rare but complicated, insti tutions must create collaborative networks in order to exchange experiences, create consensus procedures, and, if required, lead specialist consultations.

11.3 Future Directions

Translational Research: The development of radiopharmaceuticals that are optimized for use during pregnancy must continue. These ought to have higher diagnostic specificity, quicker clearance, and less placental translocation. There are encouraging prospects in this field thanks to research in peptide radiopharmaceuticals and nanomedicine.

Emerging Technologies: Personalized, more accurate risk assessment tools can be obtained by incorporating AI and machine learning into protocol optimization and fetal dosimetry. PET/MRI and other hybrid imaging technologies may be able to lower radiation exposure without sacrificing diagnostic quality.

Harmonized Regulatory Frameworks: Creating globally harmonized regulatory frameworks would encourage cooperative research and make it easier to apply best practices consistently. Given the global scope of contemporary medicine and patients' ability to move across various healthcare systems, this is particularly crucial.

11.4 Final Message

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Nuclear medicine can offer vital diagnostic information during pregnancy with manageable fetal hazards if it is well justified and carried out according to optimal guidelines. Strict adherence to radiation safety guidelines, the use of modern dosimetry techniques, and compassionate, open communication with patients are essential for success.

With exciting scientific, methodological, and technical advancements, the subject is still developing quickly. The basic idea is still the same, though: every choice must be supported by a thorough analysis of the risk-benefit ratio, accounting for the particular circumstances of each patient and using the best available techniques to safeguard the mother and the fetus.

In order to lead future best practices in this crucial area of medicine, healthcare providers need to stay abreast of these discoveries, apply evidence-based protocols, and add to the body of knowledge.

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