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Fetal Radiation Dose Calculations

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Fetal Radiation Dose Calculations

1.0 Introduction

Pregnant women are sometimes exposed to ionizing radiation in the course of medical examinations (diagnostic x-ray and nuclear medicine), from radiation therapy, or in the course of work at facilities that possess/use radioactive materials or radiation-generating equipment. These exposures may be intentional or inadvertent, the latter occurring most often during undiscovered pregnancies. When such exposures occur, and fetal dosimetry is not available, it is important to be able to provide an estimate of the radiation dose to the fetus from the procedure, incident, or work-related exposure. This estimate may be requested by the mother, the mother's physician, an involved institution, or a regulatory authority and often will be used to assist in understanding the radiation risks incurred.

This standard attempts to summarize current best methods for estimating radiation dose to the fetus. Due to lack of available data in different areas and accuracy of available models, considerable uncertainty may still exist in various scenarios and results. Many calculations are based only on the amount of data available and not on data specific to the individual in question. The user must be aware of and understand the implications of the level of accuracy of any fetal dose estimate.

1.1 Purpose and Scope

Radiology and nuclear medicine physicians, health physicists, medical physicists, radiation safety officers, regulators, and any others with the responsibility for estimating fetal dose should use the methods and numerical estimates shown in the sections of this standard for estimating radiation doses to exposed or potentially exposed pregnant subjects. Anyone employing this document should understand and take into consideration the uncertainties in applying model-based dose values to specific individuals and allow for these uncertainties in interpreting the results and discussing them with the potentially exposed subject and administrative, regulatory, or other personnel. The information provided in Section 6 should be

used to evaluate the potential risks of any doses calculated.

A recent article (Shiralkar et al. 2003) noted that some physicians might have a weak understanding of radiation doses received from standard radiological examinations. Consultation with a facility radiation safety officer or other knowledgeable physicist, in conjunction with proper use of this standard, is strongly encouraged and should provide the most accurate estimate of uterine/fetal dose available from the current literature. This standard identifies acceptable methods for assessment of fetal absorbed dose from medical examinations, radiation therapy, and occupational exposures.

1.2 Guidance

Specifically, this standard includes the following guidance:

- Estimating fetal dose from radiation therapy procedures
- Estimating fetal dose from nuclear medicine procedures
- Estimating fetal dose from diagnostic radiology procedures
- Estimating fetal dose from occupational exposures
- Interpreting results and communicating their significance to the pregnant woman and/or her physician

This document uses the SI unit system for reporting results, which is now international practice. Some conversions from previously reported quantities are provided here:

$$\begin{aligned}1 \text{ Ci} &= 3.7 \times 10^{10} \text{ Bq} \\1 \text{ mCi} &= 37 \text{ MBq} \\1 \text{ Gy} &= 100 \text{ rad} \\10 \text{ mGy} &= 1 \text{ rad} \\ \text{mGy/MBq} \times 3.7 &\equiv \text{rad/mCi}\end{aligned}$$

The generic term *dose* will be used in this document to refer to absorbed dose (Gy) and to equivalent dose (Sv).

1.3 References for Section 1

Shiralkar S, Rennie A, Snow M, Galland RB, Lewis MH, Gower-Thomas K. Doctors' knowledge of radiation exposure: questionnaire study. *Br Med J* 327:371–2; 2003.

2.0 Fetal Dose from Radiotherapy

2.1 Introduction

As mentioned previously, pregnant women are sometimes exposed to ionizing radiation in the course of medical treatments from radiation therapy. Generalized data and procedures will be presented to assist in the planning and execution of radiation therapy. Data presented are summarized from the American Association of Medical Physicists in Medicine Task Group Report No. 36 (Stovall et al. 1995) and are general in nature and should not be assumed to adequately characterize all vendors' radiation therapy machines. All such data must be interpreted or measured by a qualified medical physicist.

Photon Intensity Modulated Radiation Therapy (IMRT) will not be addressed as a separate topic; the procedures described for other photon treatments are applicable for IMRT and should be carefully measured by a medical physicist. Additionally, the physician and medical physicist should recognize the increasing role of Computed Tomography (CT) in radiation therapy and carefully review the Diagnostic Radiology section of this standard to effectively estimate fetal dose from such procedures.

This section will not address the biological effects of fetal irradiation. These effects are reviewed in Section 6 in this standard. However, the severity and frequency of adverse effects increase with total dose. Therefore, reduction of fetal dose to a level that as is as low as reasonably achievable is of course advisable to reduce the potential risks to the fetus.

The proper treatment of pregnant women with radiation requires advanced consultation between the radiation oncologist, medical oncologist, obstetrician and medical physicist.

Special devices to shield the fetus are often only available at large medical institutions, where only a few such patients may be treated annually. As such, technical resources must be allocated to prepare for these patients or they should be referred to those institutions best equipped to manage their treatment.

2.2 Radiation Dose Peripheral to the Planned Treatment Volume

Radiation dose outside or peripheral to a treatment volume is the result of photon leakage from the head of the treatment machine, radiation scattered from the collimators and beam modifiers, and radiation scattered from within the patient's treatment volume. Neutrons may measurably add to the peripheral doses for photon energies greater than 10 MeV. Collimator scatter accounts for approximately one-third of the peripheral dose and predominates near the edge of the treatment volume, while at greater distances treatment unit head leakage predominates (Green et al. 1983, 1985; Kase et al. 1983). As a general rule of thumb, collimator scatter plus head leakage is approximately equal to patient internal scatter. However, it should be noted that treatment head leakage might vary by a factor of two, depending upon vendor design (Fraass and van de Geijn 1983). Placing a lead shield between the fetus and the radiation source can easily reduce the collimator scatter and head leakage component of the total peripheral radiation dose (Fraass and van de Geijn 1983).

The use of wedges and other treatment beam modifiers can increase the peripheral dose by a factor of 2 to 5 (Fraass et al. 1985; Sherazi and Kase 1985; McParland 1990). As with head leakage and collimator scatter, these components can be reduced by shielding the critical area.

2.2.1 Photon Dose Outside of the Treatment Volume

Figure 2-1 is representative of the radiation dose expected peripheral to the desired treatment volume, as measured without the use of special shielding (Stovall et al. 1995). The AAPM Task Group Report on Fetal Dose provides additional such figures for photon energies ranging from 60Co to 25 MeV (Stovall et al. 1995). Distance from the edge of the treatment volume dominates peripheral radiation dose, decreasing approximately exponentially

with increasing distance. The absolute peripheral radiation dose will increase with increasing treatment volume due to increased internal scatter (Stovall et al. 1995). Published data indicate that the change in peripheral dose with depth is small for photon energies greater than 4 MeV (Fraas and de Geijn 1983; Kase et al. 1983; McParland 1990; Stovall et al. 1995). The exception to this similarity occurs for ^{60}Co , where head leakage dominates the dose (Fraas and de Geijn 1983; Kase et al. 1983; McParland 1990; Stovall et al. 1995).

2.2.2 Photoneutron Dose Outside of the Treatment Volume Linear accelerators with photon energies greater than 10 MeV produce neutrons in the accelerating guide, x-ray target, filters, collimators, and the patient (Almond 1979; Ing and Shore 1982; Ing et al. 1982). The neutron dose component, near the treatment volume, is less than 5% of the total peripheral dose, increasing up to 40% at a distance of 30 cm from the edge of the treatment volume (Stovall et al. 1995). The photoneutron contribution to the total dose increases as the photon energy is increased from 10 to 20 MeV, thereafter remaining approximately constant.

Specific biological data concerning the risk of neutron exposure to the fetus do not exist. The National Council on Radiation Protection (NCRP 1980) suggests that a negligible biological risk exists from the exposure to incidental neutrons from linear accelerators. The conservative choice is to treat a pregnant patient with photon energies less than 10 MeV, as long as patient care is not compromised.

2.2.3 Electron Dose Outside of the Treatment Volume Electron therapy is conceptually similar to photon treatments. Due to lower beam currents, head leakage is a smaller fraction of total peripheral dose; however, other sources of scatter (collimators, blocks, patient) continue to contribute to overall total peripheral dose. The same type of measurements and shields used for photon treatments can be used for electron treatments. The use of the photon shielding for electron treatments will reduce fetal dose by more than 50%, partly because the electron beam's inherent photon contamination has a lower average energy (Antolak et al. 1998). Currently, there is no summary of electron dose

values similar to Figure 2-1 available in the literature.

2.2.4 Brachytherapy Implants Fetal dose estimates for brachytherapy implants can be estimated using various computer or manual calculations near the radioactive implant or point dose approximations at greater distances (Nath et al. 1997). Gynecologic brachytherapy procedures typically will not be performed while the mother is pregnant, since shielding cannot be placed between the radioactive sources and the fetus. Other brachytherapy procedures (i.e., volume implant for sarcomas, eye plaques for ocular melanoma, etc.) may be appropriate if they are sufficiently distant from the fetus. The radiation oncologist, obstetrician, and medical physicist should carefully review each case. If treatment is determined to be a medical necessity, the medical physicist should estimate the fetal dose by one of the above methods and determine whether appropriate shielding can be provided to the fetus.

2.2.5 Summary Peripheral radiation dose from external radiation therapy directly depends on energy, distance from the treatment volume, treatment volume size (i.e., treatment field size), and, to a much lesser extent, depth. Patient internal and collimator scatter dominate peripheral radiation dose within 10 cm of the edge of the treatment volume. Patient internal scatter dominates in the distance of 10 to 20 cm from the edge of the treatment volume. Head leakage dominates at a distance of approximately 30 cm, where patient internal scatter and head leakage are approximately equivalent. The use of blocks and wedges may increase dose near the edge of the treatment volume by a factor of 2 to 5. It is imperative that the physicist realize that the shielding can only reduce the collimator scatter and head leakage components of peripheral dose.

2.3 Fetal Dose Estimation and Reduction

2.3.1 Dose Estimation The medical physicist is responsible for estimating the dose to the fetus. Gestational age is of primary importance to the treating physician when estimating fetal dose, as is discussed in the Biological Risk section. Typical anatomical points utilized for fetal dose estimation are the uterine fundus, symphysis pubis, and patient umbilicus (Stovall et al. 1995).

The fundus and pubis delineate the limits of the fetal position, and the umbilicus represents a generalized mid-fetal position. Fundus position moves superiorly, with regard to the pubis, as the pregnancy progresses. This position should be carefully monitored during patient treatment and taken into account when determining the total expected fetal radiation dose. Fetal orientation changes frequently, and no single point can adequately describe the location of the fetal brain or other organs.

Dose estimates often require measurements, either in water, a solid phantom, or an anthropomorphic phantom utilizing ionization chambers, diodes, or thermoluminescent dosimeters (TLD). The physicist should first estimate/measure the dose to the fetus without special shielding. Additional dose measurement should then be repeated using special shields as appropriate. Treatment modification and shielding devices are the primary methods to reduce fetal dose.

2.3.2 Modification of Treatment Techniques

Treatment modification is usually a combination of many factors, such as (1) changing treatment angles, (2) reducing the planned treatment volume (i.e., field size), (3) choosing a different energy, or (4) use of the lower collimators to define the field edge nearest the fetus.

2.3.3 Use of Special Shields

2.3.3.1 General Considerations The medical physicist must review all treatment parameters to minimize the risk of injury to the patient or personnel when using any special shielding. Shielding design must allow for treatment with anterior, posterior, and lateral orientations, above the diaphragm and the extremities. Two types of shielding arrangements will be described. Additional details may be found in the scientific literature (Stovall et al. 1995).

2.3.3.1.2 Bridge over Patient A basic shield design consists of a bridge over the patient's abdomen that supports five half-value layers of lead, allowing the patient to lie in either a supine

or prone position. The superior edge of the shield is as near as possible to the inferior edge of the treatment volume. This position easily attenuates much of the dose contribution due to head leakage and collimator scatter. For posterior treatments, the patient may lie prone on a false tabletop, with the shielding bridge placed over her back, or the lead may be supported on a shelf below the treatment couch.

2.3.3.1.3 Mobile Shields Treatment versatility can be increased by coupling the basic bridge over patient design with a frame that supports the lead such that it does not rest upon the treatment couch (Stovall et al. 1995). A vertical adjustment motor is added to allow for treatment at a source-to-skin distance of 80 to 125 cm, and appropriate wheels are attached to allow for easy movement by the treatment staff. The addition of side shielding allows for lateral treatments. The weight of such a unit may approach 200 kg; therefore, the physicist must ensure that appropriate safety procedures are in place.

For posterior treatments, a shield is designed to fit between the existing treatment couch and head of the treatment machine (Stovall et al. 1995). Although attached to the treatment couch, the combination of shield and patient weight typically will not exceed vendors' couch design limits.

2.4 Example of Estimation and Reduction of Fetal Dose

Table 2-1 demonstrates the expected fetal dose for a pregnant patient being treated for Hodgkin's disease. The fetal dose was measured in an anthropomorphic phantom using diodes and shows approximately a 50% decrease compared to the unshielded values. Additional examples may be found in the scientific literature (Yudelev et al. 1982 ; Nair et al. 1983 ; Sneed et al. 1995 ; Cygler et al. 1997 ; Antypas et al. 1998 ; Mazonakis et al. 1999 ; Podgorsak et al. 1999 ; Greskovich et al. 2000 ; Prado et al. 2000 ; Islam et al. 2001 ; Magne et al. 2001 ; Ioffe et al. 2002 ; Nuytens et al. 2002).

Table 2-1. Hodgkin's disease

Machine: Varian CI 2100C, 6 MV, 100 cm SSD
 Field configuration: Anterior and posterior mantles
 Prescribed dose: 40 Gy midline
 Therapy to be given over 6 weeks
 Gestational stage at beginning of therapy: 34 weeks
 Shielding: 5 HVL (6.7 cm) lead

	<u>Uterine</u> <u>Fundus</u>	<u>Mid-Fetus</u>	<u>Pubis</u>
Distance from nearest field edge (cm)	15.5	28.5	41.5
Dose to unshielded fetus (Gy, 10 cm depth)	0.42	0.14	0.06
Dose to shielded fetus (Gy, 10 cm depth)	0.17	0.04	0.02
Machine: Varian CI 2100C, 6 MV, 100 cm SSD			

2.5. Recommendations

Specific requirements vary for individual patients' treatments. However, the medical physicist in conjunction with the radiation oncologist should carefully review all aspects of the pregnant patient's treatment. The following are minimal considerations prior to and during the patient's treatment (Stovall et al. 1995):

1. Plan the patient's treatment normally (as if not pregnant). Modify the treatment plan as appropriate. Possible modifications include changing the treatment volume (field size and angle), selecting a different radiation energy, etc.
2. Estimate fetal dose without shielding. Use peripheral dose data measured on the specific treatment unit to be utilized. Typical points of interest are the uterine fundus, the symphysis pubis, and a midpoint (umbilicus).
3. If dose estimates in item 2 above are not acceptable, design and construct special shielding. Typically, five half-value layers of lead or equivalent is appropriate.
4. Final Treatment Plan. Measure peripheral dose in phantom utilizing treatment parameters and shielding (if applicable). Document the results and treatment setup instructions (including photographs) in the treatment plan. Discuss the set-up with the involved personnel.
5. Verify safety, including load-bearing limits of the treatment couch, structural integrity and movement of the shields, etc.
6. The physicist should be present at the time of initial treatment and be available for consultation during subsequent treatments.
7. Monitor fetal size and location throughout the course of treatment, repeating dose estimates as appropriate. Document the completion of treatment by estimating the total dose to the fetus during the course of therapy.
8. Refer the patient to another institution for treatment if appropriate.

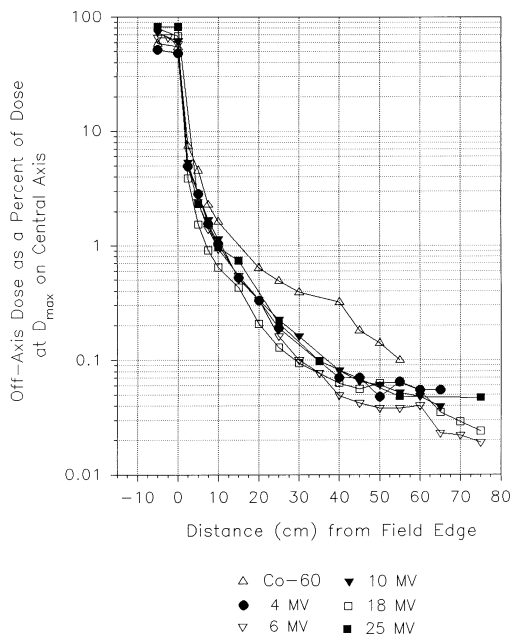


Figure 2-1. Total absorbed dose in phantom from $10 \times 10 \text{ cm}^2$ field for ^{60}Co – 25 MeV photons, at 10 cm depth, normalized to 100% on the central axis at depth of maximum dose (from Stovall et al. 1995).

2.6. References for Section 2

- Almond P.R. Neutron leakage from current machines. In: Proc. Conf. on Neutrons from Electron Medical Accelerators; Washington, DC: National Bureau of Standards; Spec. Publ. 544; 1979: 129–138.
- Antolak JA, Strom EA. Fetal dose estimates for electron-beam treatment to the chest wall of a pregnant patient. *Med Phys* 25:2388–2391; 1998.
- Antypas C, Sandilos P, Kouvaris J, Balafouta E, Karinou E, Kollaros N, Vlahos L. Fetal dose evaluation during breast cancer radiotherapy. *Int J Radiat Oncol Biol Phys* 40:995–999; 1998.
- Cohen Y, Thatcher M, Robinson E. Radiotherapy in pregnancy. *Radiol Clin Biol* 42:34–39; 1973.
- Cygler J, Ding GX, Kendal W, Cross P. Fetal dose for a patient undergoing mantle field irradiation for Hodgkin's disease. *Med Dosim* 22:135–137; 1997.
- Fraass BA, Roberson PL, Lichter AS. Dose to the contralateral breast due to primary breast irradiation. *Int J Radiat Oncol Biol Phys* 11:485–497; 1985.
- Fraass BA, van de Geijn J. Peripheral dose from megavolt beams. *Med Phys* 10:809–818; 1983.
- Greene D, Chu GL, Thomas DW. Dose levels outside radiotherapy beams. *Br J Radiol* 56:543–550; 1983.
- Greene D, Karup PGG, Sims C, Taylor RJ. Dose levels outside radiotherapy beams. *Br J Radiol* 58:453–456; 1985.
- Greskovich JF, Macklis RM. Radiation therapy in pregnancy: risk calculation and risk minimization. *Sem Oncol* 27:633–645; 2000.
- Ing H, Nelson WR, Shore RA. Unwanted photon and neutron radiation resulting from collimated photon beams interacting with the body of radiotherapy patients. *Med Phys* 9:27–33; 1982.
- Ing H, Shore RA. Unwanted radiation produced by leakage neutrons from medical electron accelerators. *Med Phys* 9:34–36; 1982.
- Ioffe V, Hudes RS, Shepard D, Simard JM, Chin LS, Yu C. Fetal and ovarian radiation dose in patients undergoing gamma knife radiosurgery. *Surg Neuro* 58:32–41; 2002.
- Islam MK, Saeedi F, Al-Rajhi N. A simplified approach for limiting fetal dose during radiation therapy of pregnant patients. *Int J Radiat Oncol Biol Phys* 49:1469–1473; 2001.
- Kase KR, Svensson GK, Wolbarst AB, Marks MA. Measurements of dose from secondary radiation outside a treatment field. *Int J Radiat Oncol Biol Phys* 9:1177–1183; 1983.
- Keller B, Mathewson C, Rubin P. Scattered radiation doses as a function of x-ray energy. *Radiology* 111:447–449; 1974.
- Magne N, Marcie S, Pignol JP, Casagrande F, Lagrange JL. Radiotherapy for a solitary brain metastasis during pregnancy: a method for reducing fetal dose. *Br J Radiol* 74:638–641; 2001.
- Mazonakis M, Dailakis J, Varveris H, Theoharopoulos N, Gourtsoyannis N. A method of estimating fetal dose during brain radiation therapy. *Int J Radiat Oncol Biol Phys* 44:455–459; 1999.
- McKinlay AF. Thermoluminescence dosimetry. Bristol, UK: Hilger; 1981.
- McParland BJ. Peripheral doses of two linear accelerators employing universal wedges. *Br J Radiol* 63:295–298; 1990.
- Nair RP, Nair TK, El-Akkad S. Evaluation of fetal dose from megavoltage irradiation of the knee

- and neonate followup. *Med Phys* 10:862–865; 1983.
- Nath R, Anderson, LL, Meli JA, Olch AJ, Stitt JA, Williamson JF. Code of practice for brachytherapy physics: report of the AAPM Radiation Therapy Committee Task Group No. 56. *Med Phys* 10:1557–1598; 1997.
- Nath R, Epp ER, Laughlin JS, Swanson WP, Bond VP. Neutrons from high-energy x-ray medical accelerators: an estimate of risk to the radiotherapy patient. *Med Phys* 11:231–241; 1984.
- National Council on Radiation Protection. Influence of dose and its distribution in time on dose-reponse relationships for low-LET radiations. Bethesda, MD: NCRP; Rep. No. 64; 1980.
- Nuyttens JJ, Prado KL, Jenrette JM, Williams TE. Fetal dose during radiotherapy: clinical implementation and review of the literature. *Cancer Radio* 6:352–357; 2002.
- O'Connor M, Blackwell CR, Kisrow K. Fetal dose for patients undergoing mantle irradiation for Hodgkin's disease. *Med Dosim* 12:9–11; 1987.
- Podgorsak MB, Meiler RJ, Kowal H, Kishel SP, Orner JB. Technical management of a pregnant patient undergoing radiation therapy to the head and neck. *Med Dosim* 24:121–128; 1999.
- Prado KL, Nelson SJ, Nuyttens JJ, Williams TE, Vanek KN. Clinical implementation of the AAPM Task Group 36 recommendations on fetal dose from radiotherapy with photon beams: a head and neck irradiation case report. *J Appl Clin Med Phys* 1:1–7; 2000.
- Sherazi S, Kase KR. Measurements of dose from secondary radiation outside a treatment field: effects of wedges and blocks. *Int J Radiat Oncol Biol Phys* 11:2171–2176; 1985.
- Sneed PK, Albright NW, Wara WM, Prados MD, Wilson CB. Fetal dose estimates for radiotherapy of brain tumors during pregnancy. *Int J Radiat Oncol Biol Phys* 32:823–830; 1995.
- Stovall M, Blackwell CR, Cundiff J, Novack DH, Palta JR, Wagner LK, Webster EW, Shalek RJ. Fetal dose from radiotherapy with photon beams: report of AAPM Radiation Therapy Committee Task Group No. 36. *Med Phys* Jan 22(1):63–82; 1995 [review]. Erratum in: *Med Phys* Aug 22(8):1353–1354; 1995.
- Woo SY, Fuller LM, Cundiff JH, Bondy ML, Hagemester FB, McLaughlin P, Velasquez WS, Swan F, Rodriguez MA, Cabanillas R, Allen PK, Carpenter, RJ, Jr. Radiotherapy during pregnancy for clinical stages II-IIA Hodgkin's disease. *Int J Radiat Oncol Biol Phys* 23:407–412; 1992.
- Yudelev M, Tatcher M, Mandelzweig Y, Kuten A. Fetal dose in electron therapy of pregnant patients using a Philips SI75/10 linear accelerator. *Br J Radiol* 55:669–671; 1982.

3.0 Dose to the Fetus in Nuclear Medicine

3.1 Introduction

Estimation of radiation dose to the fetus in nuclear medicine is a commonly encountered problem. As much as nuclear medicine departments try to avoid the administration of radiopharmaceuticals to pregnant women, such situations inevitably occur, either due to administrations involving undiscovered pregnancies or involving known pregnancies, but only in cases in which the administration of radioactive material is not contraindicated due to the risks involved. Should an administration occur, reliable estimates of the dose received by the fetus are needed to aid the nuclear medicine physician in assessing the risk, advising the

patient, and providing information for hospital records (for general record keeping, response to possible litigation, and other purposes).

Administration of radiopharmaceuticals in undiscovered pregnancies may be due to a number of causes, including poor investigative techniques by the nuclear medicine department staff (lack of proper signage, questioning of potentially pregnant patients, etc.), intentional or inadvertent misinformation given by the patient and/or family to the staff, inaccurate test results, combinations of these items, or other factors. Administrations in undiscovered pregnancies occur most typically early in gestation, which is helpful in simplifying both the geometric models employed as well as the evaluation of placental crossover.

Mossman (1985) showed that, because of the small risks involved, it is probably not cost-

effective to administer pregnancy tests to all women of childbearing age that receive radiodiagnostic examinations, including radiopharmaceuticals. Many, but not all, nuclear medicine departments administer pregnancy tests to all patients who will receive therapeutic administrations, particularly of ^{131}I NaI (Russell et al. 1997b). For diagnostic studies, usually the staff depends on some combination of signage and interrogation of the patient (Russell et al. 1997b).

Dose estimates are needed, however, at all stages of pregnancy for many radiopharmaceuticals, because the number and complexity of situations that can occur is large, and it is difficult to anticipate the future based on experience gained to date. In this document, we review the existing knowledge regarding the available dose calculational techniques, radiopharmaceuticals commonly administered to women of childbearing age, physical and biokinetic models for these calculations, numerical estimates of dose to the fetus and fetal organs, dose reduction techniques, and recommendations for advising the patient about the risks of any doses received.

3.2 Dose Calculation Methodology

Calculation of dose to either the entire fetus or to individual fetal organs, as with all internal dose applications, involves combining an understanding of the biokinetics of the radiopharmaceutical within the body (of the mother and/or fetus) with physical quantities, usually based on Monte Carlo simulations of radiation transport, that relate biokinetics to dose. Specifically, the result of a successful biokinetic analysis is an estimate of the number of disintegrations that occurred in all significant source regions within the body, and the physical quantities provide the dose to target organs per disintegration in each source region. Thus, for a given radiopharmaceutical, one must identify which are the significant source regions and through calculation estimate the number of disintegrations that occur in each, identify the important target regions in the problem (usually the source regions plus a number of other regions of radiobiological interest), then apply the appropriate dose conversion factors for each source–target combination until all contributions from each source are summed for each target

and an estimate of total dose to each target region is obtained. There are a number of published dose calculational methodologies available; all employ exactly the same basic modeling assumptions but use different nomenclature to express the variables and results (Stabin 1996a). In nuclear medicine, the most commonly employed method is that derived by the Medical Internal Radiation Dose (MIRD) Committee of the Society of Nuclear Medicine (Loevinger et al. 1988). Their scheme is perhaps most clearly shown as:

$$D_{r_k} = \sum_h \tilde{A}_h S(r_k \leftarrow r_h) \quad \text{Eq 3.1}$$

where

D_{r_k} = the dose to target region r_k (Gy),
 $\tilde{A}_h$ = the cumulated activity (i.e., the number of disintegrations that occurred) in source region r_h (Bq-s),
 $S(r_k \leftarrow r_h)$ = the “S value,” which is the dose conversion factor giving the dose to target region r_k per disintegration in source region r_h (Gy/Bq-s).

This equation is also sometimes shown as:

$$D_{r_k} = A_0 \sum_h \tau_h S(r_k \leftarrow r_h) \quad \text{Eq 3.2}$$

where

A_0 = the initial activity administered to the subject (Bq), and
 τ_h = the number of disintegrations in source region h per unit administered activity (Bq-s/Bq).
 Mathematically, $\tau_h = \tilde{A}_h/A_0$.

The quantity τ_h in the MIRD system is referred to as “residence time,” although the use of this term is not completely appropriate, given the fact that the quantity is not a measure of time (notwithstanding the units after cancellation of like terms) and given its interpretation in other scientific disciplines. If thought of as the number of disintegrations normalized to the amount of activity administered, it will be properly interpreted.

3.3 Radiopharmaceuticals Commonly Administered to Women of Childbearing Age

Russell et al. (1997b) conducted a survey to determine the diagnostic nuclear medicine procedures most commonly employed in women of childbearing age. "Childbearing age" for this survey was defined to be 13 to 45 years of age. Thirty medical institutions of various sizes and missions were surveyed. Twenty-six of the institutions responded to the questionnaire either completely or in part. The patient workload of the nuclear medicine department at each institution per year was requested. Eleven percent of the institutions had fewer than 4,000 patients per year, 39% had between 4,000 and 6,000, 31% had between 6,000 and 8,000, 8% had between 8,000 and 10,000, and 11% had greater than 10,000. Over half of the institutions reported that 45 to 65% of the patient population were females of childbearing age. This survey was not designed to be statistically representative of all nuclear medicine institutions; the results thus are not to be taken as authoritative. Nonetheless, the results are helpful in understanding some facts about administration of radiopharmaceuticals to women of childbearing age at the time of the study.

Their results showed that the most frequently administered radiopharmaceuticals were (in the order from the most commonly used to the least commonly used):

1. ^{99m}Tc Methylene Diphosphonate (MDP)
2. ^{99m}Tc Macroaggregated Albumin (MAA)
3. ^{123}I Sodium Iodide
4. ^{67}Ga Citrate
5. ^{133}Xe (gas)
6. ^{201}Tl Chloride
7. ^{99m}Tc Benzoylmercaptoacetyl-triglycerine (MAG3)
8. ^{99m}Tc Methoxyisobutylisonitrile (MIBI)
9. ^{99m}Tc Mebrofenin
10. ^{99m}Tc Diethylenetriamine-pentaacetic Acid (DTPA)
11. ^{99m}Tc DTPA Aerosol
12. ^{99m}Tc White Blood Cells
13. ^{99m}Tc Sulfur Colloid
14. ^{99m}Tc Hydroxymethylene Diphosphonate (HDP)
15. ^{131}I Sodium Iodide
16. ^{99m}Tc Pertechnetate

17. ^{99m}Tc Disofenin
18. ^{111}In White Blood Cells
19. ^{99m}Tc Red Blood Cells

3.4 Physical Models

3.4.1 The Pregnant Female Phantom Series

Stabin et al. (1995) developed anthropomorphic models representing the pregnant woman at 3, 6, and 9 months of gestation and gave a model for the nonpregnant adult female (which can be used to model the woman in early pregnancy through study of the dose to the non gravid uterus). The models of the female body at various stages of pregnancy were derived from consideration of the physical changes that occur in the uterus and surrounding organs. Specific absorbed fractions (SAFs) for these models were derived through radiation transport studies employing Monte Carlo and buildup factor techniques and can be used with various sources of decay data to determine the S-values (dose conversion factors) needed for the calculation of dose estimates.

3.4.2 Kinetic Models

3.4.2.1 Models for Pharmacokinetics in the Mother

Russell et al. (1997b) also performed an evaluation of the best available biokinetic models for many radiopharmaceuticals, including but not limited to the 19 radiopharmaceuticals above, and tabulated values of source organ residence times. They reviewed the available biokinetic models that predicted placental crossover of radiopharmaceuticals, from either animal or human studies. They concluded, however, that "only a small number of the radiopharmaceuticals that may be administered to women of childbearing years have been studied to determine potential placental and fetal uptakes." Thus, although combatting a scarcity of reliable information, they concluded that estimates of fetal dose using existing biokinetic and physical models was better guidance than no guidance at all and published dose estimates for the fetus at all stages of pregnancy for many radiopharmaceuticals, including those for which information on placental crossover was available, and those for which such information was not available. For the vast majority of

radiopharmaceuticals, they used standard biokinetic models for the radiopharmaceutical to determine the number of disintegrations that occurred in the mother's organs and calculated dose to the fetus using the Stabin et al. pregnant female models, as implemented in the MIRDOSE 3 computer program (Stabin 1996). In cases in which information was available on placental crossover from animal or human studies, activity was also assigned to the fetus and/or placenta. In a few cases, a biokinetic model that linked the maternal and fetal systems was used. In general, however, standard biokinetic models were employed, with no accounting for possible changes in biokinetics that might occur during pregnancy. In the cases in which fetal or placental activity was assigned, this was done as a function of gestation, but without any changes in the mother's activity distribution otherwise.

There are a number of biological changes that occur during pregnancy that could possibly affect the biokinetics of radiopharmaceuticals. Changes have been documented (Niswander 1982) in:

1. The cardiovascular system—including increases in cardiac output (30–50%), increases in heart rate (up to 10–15 beats/min), increases in stroke volume (20–40%), increases in blood volume (20–100%), and a possible decrease in blood pressure.
2. The renal system—including an increase in the length of the kidneys (up to 1 cm), increased dilation of the renal pelvis and calyces and the ureters, increases in the glomerular filtration rate (30–50%), increases in the filtration fraction, changes in renal blood flow, and increases in sodium reabsorption (a consequence of the changes in some of the other variables mentioned).
3. The circulatory system—including induction of anemia, in various forms:
 - a. "physiologic anemia," due to the increase in plasma volume relative to the number of erythrocytes,
 - b. iron-deficiency anemia, due to a change in iron demand by the placenta and possible decrease in absorption from the small intestine,
 - c. folic acid deficiency anemia, due to shortages in diet or malabsorption,
 - d. infection-caused anemia.

4. The respiratory system—including increases in oxygen consumption (~25%), minute ventilation (~40%), and, consequently, in CO₂ production, as well as a compensatory increased renal bicarbonate excretion.
5. The gastrointestinal system—including induction of various liver diseases and jaundice, changes in appetite, induction of esophageal reflux, decreased motility and acid secretion in the stomach, and possible decreased motility in the small and large intestines.
6. The endocrine system—including induction of diabetes, induction of hyper- or hypothyroidism, induction of adrenal hyper- or hypofunction, induction of pituitary hypofunction, and induction of hyper- or hypoparathyroidism.

In addition, some diseases, infections, neurologic disorders, and other effects are more pronounced or more likely to appear in pregnancy. All of these factors could conceivably affect the uptake and/or clearance of a radiopharmaceutical, and thus affect the number of disintegrations occurring in the various source organs. However, documentation of any influence of such changes on the biodistribution and kinetics of radiopharmaceuticals is lacking.

3.4.2.2 Models for Placental Crossover As noted above, data regarding the placental crossover of radiopharmaceuticals is quite limited. There are a number of animal studies, performed by various investigators in various animal species. There are some limited data on the placental crossover of ¹³¹I sodium iodide from human studies, some involving measurements in newborns or in situations involving therapeutic abortion. In the case of animal studies, there are uncertainties associated with the extrapolation of the measured concentrations to humans, of the correlation of the stage of gestation in the animal to that in a human, and of the various animal species used by different investigators. In the case of human studies, usually the data are very sparse and gathered at different times and under different situations (obviously, the data do

not come from controlled studies, but are serendipitously gathered as is possible). Table 3-1 summarizes the information gathered by

Russell et al. (1997a) regarding the availability of such data for use in radiation dose estimates.

Table 3-1. Models for placental crossover of radiopharmaceuticals and data sources available in the literature (from Russell et al. 1997a))

Radiopharmaceutical	Type of data found in literature (human or animal)	Data employed*	Stage(s) of gestation**	Comments
^{99m} Tc Methylene Diphosphonate (MDP)	Human and animal	Fetal and placental concentrations – guinea pigs	3 and 9 mo	
^{99m} Tc Macro Aggregated Albumin (MAA)	Animal	Fetal and placental activity – guinea pigs	3, 6, and 9 mo	
¹²³ I Sodium Iodide	Human	Fetal and fetal thyroid measurements – coupled to maternal compartment model	Early, 3, 6, and 9 mo	The best developed models – compartment models linking maternal and fetal systems
⁶⁷ Ga Citrate	Human and animal	Fetal and placental activity – rabbits, coupled to maternal compartment model	3, 6, and 9 mo	A well-developed compartment model linking maternal and fetal systems
²⁰¹ Tl Chloride	Animal	Data on guinea pigs, but none usable		
^{99m} Tc Diethylenetriaminepenta-acetic Acid (DTPA)	Human and animal	Fetal and placental activity – rats	3, 6, and 9 mo	
^{99m} Tc DTPA Aerosol	Human and animal	Fetal and placental activity – rats	3, 6, and 9 mo	Model for injected DTPA used; fraction of inhaled DTPA reaching bloodstream determined from kinetic model
^{99m} Tc Sulfur Colloid	Animal data	Fetal activity – rabbits	3, 6, and 9 mo	
^{99m} Tc Hydroxymethylene Diphosphonate	Animal data	Fetal and placental concentrations – guinea pigs	3 and 9 mo	Data for MDP used
¹³¹ I Sodium Iodide	Human	Fetal and fetal thyroid measurements – coupled to maternal compartment model	Early, 3, 6, and 9 mo	The best developed models – compartment models linking maternal and fetal systems
^{99m} Tc Pyrophosphate (PYP)	Animal	Fetal and placental activity – mice	3 mo	
^{99m} Tc 2,3 Dimercaptosuccinic Acid (DMSA)	Animal	Fetal and placental activity – mice	9 mo	
^{99m} Tc Glucoheptonate	Animal	Placental and fetal activity – guinea pigs		

*Data actually used in calculating dose estimates.

**Estimated human stage of gestation.

Should activity cross the placenta, the activity in the fetus will most likely not be distributed uniformly, as assumed by Russell et al. and most other investigators, but will probably have some distribution within the fetal organs that mimics that in the mother to some degree, perhaps depending on the stage of gestation. To calculate the contribution of dose from the mother's organs, only an average dose to the fetus can be calculated, since the fetus moves around within the uterus during pregnancy, and an exact anatomical location of each organ relative to the mother's body cannot be determined. Within the fetus itself, the organ geometry can be defined, and it is probable that in most cases an organ with a significant uptake of a radiopharmaceutical will deliver the great majority of its own dose to itself (i.e. cross-irradiation will not be very significant). Thus, once an amount of activity crossing the placenta is determined, one might assign a dose to the fetal organs using the distribution parameters from the standard models and the fetal organ masses, estimating only self-dose in the organs that have a significant uptake. Two complications may compromise the accuracy of such a calculation:

- a) The activity distribution pattern and concentrations in the fetal tissues may not be the same as in an adult. For example,

Watson (1992) found that the concentration of ^{131}I NaI in the fetal thyroid may be considerably higher (up to 7.5 times higher) than that in the mother's thyroid at particular times in gestation.

- b) The activity that crosses the placenta may or may not be in the same form as the activity administered to the mother.

Thus, the use of the fetal organ models to calculate individual organ doses in the fetus is limited in usefulness unless reliable models of fetal biokinetics become available, which is highly unlikely, even with the use of animal models. Calculation of total fetal dose can be performed in a fairly reliable way, using existing physical models of the maternal and fetal anatomy. Since small percentages of the administered activity customarily cross the placenta, at least based on the activity we have from animal studies, the dose to individual fetal organs is likely to be low. The notable exception to this, of course is for ^{131}I NaI, for which the dose to the fetal thyroid can be the most important factor in assessing fetal dose and risk (Watson 1992). Table 3-2 shows the estimates of dose to the fetal thyroid per unit administered activity for ^{123}I , ^{124}I , ^{125}I , and ^{131}I NaI (Watson 1992).

Table 3-2. Absorbed dose in fetal thyroid from radionuclides administered to the pregnant woman (mGy to fetal thyroid per MBq administered to the mother), from Watson (1992)

Gestational age (mo)	^{123}I	^{124}I	^{125}I	^{131}I
3	2.7	24	290	230
4	2.6	27	240	260
5	6.4	76	280	580
6	6.4	100	210	550
7	4.1	96	160	390
8	4.0	110	150	350
9	2.9	99	120	270

This is probably the most reliable biokinetic model for dose to any fetal organ; nonetheless, the data on fetal thyroid uptake are very limited, and existing data from different sources were

not always in good agreement (Watson 1992). Thus, prospects are not good for obtaining reliable data for use in calculating fetal organ doses for this or other radiopharmaceuticals.

3.5 Radiation Dose Estimates

The following tables, reproduced directly from Russell et al. (1997b), show their recommended dose estimates at all stages of pregnancy for many (over 80) radiopharmaceuticals. Compounds for which some information was available regarding placental crossover are shown in shaded rows. It is very important to remember that these dose estimates depend directly on the residence times assumed for each radiopharmaceutical (as catalogued in the article by Russell et al., but not reproduced here). Any changes in the biokinetic models

assumed will cause a change in the dose estimates calculated. These tables give the dose to the fetus per unit activity administered to the mother. In the majority of cases, this activity is given by injection, but in a few cases the activity is ingested or inhaled (xenon gases, ^{99m}Tc -labeled aerosols, etc.). It is very important in the latter case to remember that the numbers in this table give the dose per unit activity *inhaled by the mother*. This can be substantially different from the amount of activity *introduced into a device* (spirometer or other container), so care must be taken in applying the values to patients.

Table 3-3. Absorbed dose estimates to the embryo/fetus per unit activity of radiopharmaceutical administered to the mother (shading indicates maternal and fetal self dose contributions) (from Russell et al. (1997b)).

Radiopharmaceutical	Early mGy/MBq*	3 Month mGy/MBq*	6 Month mGy/MBq*	9 Month mGy/MBq*
^{57}Co Vitamin B-1, Normal-Flushing 1.0×10^0	6.8×10^{-1}	8.4×10^{-1}	8.8×10^{-1}	
^{57}Co Vitamin B-12, Normal-No Flushing	1.5×10^0	1.0×10^0	1.2×10^0	1.3×10^0
^{57}Co Vitamin B-12, PA- Flushing	2.1×10^{-1}	1.7×10^{-1}	1.7×10^{-1}	1.5×10^{-1}
^{57}Co Vitamin B-12, PA- No Flushing	2.8×10^{-1}	2.1×10^{-1}	2.2×10^{-1}	2.0×10^{-1}
^{58}Co Vitamin B-12, Normal Flushing	2.5×10^0	1.9×10^0	2.1×10^0	2.1×10^0
^{58}Co Vitamin B-12, Normal-No Flushing	3.7×10^0	2.8×10^0	3.1×10^0	3.1×10^0
^{58}Co Vitamin B-12, PA-Flushing	8.3×10^{-1}	7.4×10^{-1}	6.4×10^{-1}	4.8×10^{-1}
^{58}Co Vitamin B-12, PA-No Flushing 9.8×10^{-1}	8.5×10^{-1}	7.6×10^{-1}	6.0×10^{-1}	
^{60}Co Vitamin B-12, Normal Flushing	3.7×10^1	2.8×10^1	3.1×10^1	3.2×10^1
^{60}Co Vitamin B-12, Normal-No Flushing	5.5×10^1	4.2×10^1	4.7×10^1	4.7×10^1
^{60}Co Vitamin B-12, PA-Flushing	5.9×10^0	4.7×10^0	4.8×10^0	4.5×10^0
^{60}Co Vitamin B-12, PA-No Flushing 8.3×10^0	6.5×10^0	6.8×10^0	6.5×10^0	
^{18}F FDG†	2.2×10^{-2}	2.2×10^{-2}	1.7×10^{-2}	1.7×10^{-2}
^{18}F Sodium Fluoride	2.2×10^{-2}	1.7×10^{-2}	7.5×10^{-3}	6.8×10^{-3}
^{67}Ga Citrate	9.3×10^{-2}	2.0×10^{-1}	1.8×10^{-1}	1.3×10^{-1}
^{123}I Hippuran	3.1×10^{-2}	2.4×10^{-2}	8.4×10^{-3}	7.9×10^{-3}
^{123}I IMP	1.9×10^{-2}	1.1×10^{-2}	7.1×10^{-3}	5.9×10^{-3}
^{123}I MIBG	1.8×10^{-2}	1.2×10^{-2}	6.8×10^{-3}	6.2×10^{-3}
^{123}I Sodium Iodide	2.0×10^{-2}	1.4×10^{-2}	1.1×10^{-2}	9.8×10^{-3}
^{124}I Sodium Iodide	1.4×10^{-1}	1.0×10^{-1}	5.9×10^{-2}	4.6×10^{-2}
^{125}I HSA	2.5×10^{-1}	7.8×10^{-2}	3.8×10^{-2}	2.6×10^{-2}
^{125}I IMP	3.2×10^{-2}	1.3×10^{-2}	4.8×10^{-3}	3.6×10^{-3}
^{125}I MIBG	2.6×10^{-2}	1.1×10^{-2}	4.1×10^{-3}	3.4×10^{-3}
^{125}I Sodium Iodide	1.8×10^{-2}	9.5×10^{-3}	3.5×10^{-3}	2.3×10^{-3}
^{126}I Sodium Iodide	7.8×10^{-2}	5.1×10^{-2}	3.2×10^{-2}	2.6×10^{-2}
^{130}I Sodium Iodide	1.8×10^{-1}	1.3×10^{-1}	7.6×10^{-2}	5.7×10^{-2}
^{131}I Hippuran	6.4×10^{-2}	5.0×10^{-2}	1.9×10^{-2}	1.8×10^{-2}
^{131}I HSA	5.2×10^{-1}	1.8×10^{-1}	1.6×10^{-1}	1.3×10^{-1}
^{131}I MAA	6.7×10^{-2}	4.2×10^{-2}	4.0×10^{-2}	4.2×10^{-2}
^{131}I MIBG	1.1×10^{-1}	5.4×10^{-2}	3.8×10^{-2}	3.5×10^{-2}
^{131}I Sodium Iodide	7.2×10^{-2}	6.8×10^{-2}	2.3×10^{-1}	2.7×10^{-1}
^{131}I Rose Bengal	2.2×10^{-1}	2.2×10^{-1}	1.6×10^{-1}	9.0×10^{-2}
^{111}In DTPA	6.5×10^{-2}	4.8×10^{-2}	2.0×10^{-2}	1.8×10^{-2}
^{111}In Pentetretotide	8.2×10^{-2}	6.0×10^{-2}	3.5×10^{-2}	3.1×10^{-2}
^{111}In Platelets	1.7×10^{-1}	1.1×10^{-1}	9.9×10^{-2}	8.9×10^{-2}

¹¹¹ In Red Blood Cells	2.2x10 ⁻¹	1.3x10 ⁻¹	1.1x10 ⁻¹	8.6x10 ⁻²
¹¹¹ In White Blood Cells	1.3x10 ⁻¹	9.6x10 ⁻²	9.6x10 ⁻²	9.4x10 ⁻²
^{99m} Tc Albumin Microspheres	4.1x10 ⁻³	3.0x10 ⁻³	2.5x10 ⁻³	2.1x10 ⁻³
^{99m} Tc Disofenin	1.7x10 ⁻²	1.5x10 ⁻²	1.2x10 ⁻²	6.7x10 ⁻³
^{99m} Tc DMSA	5.1x10 ⁻³	4.7x10 ⁻³	4.0x10 ⁻³	3.4x10 ⁻³
^{99m} Tc DTPA	1.2x10 ⁻²	8.7x10 ⁻³	4.1x10 ⁻³	4.7x10 ⁻³
^{99m} Tc DTPA Aerosol	5.8x10 ⁻³	4.3x10 ⁻³	2.3x10 ⁻³	3.0x10 ⁻³
^{99m} Tc Glucoheptonate	1.2x10 ⁻²	1.1x10 ⁻²	5.3x10 ⁻³	4.6x10 ⁻³
^{99m} Tc HDP	5.2x10 ⁻³	5.4x10 ⁻³	3.0x10 ⁻³	2.5x10 ⁻³
^{99m} Tc HEDP	7.2x10 ⁻³	5.2x10 ⁻³	2.7x10 ⁻³	2.4x10 ⁻³
^{99m} Tc HMPAO	8.7x10 ⁻³	6.7x10 ⁻³	4.8x10 ⁻³	3.6x10 ⁻³
^{99m} Tc Human Serum Albumin	5.1x10 ⁻³	3.0x10 ⁻³	2.6x10 ⁻³	2.2x10 ⁻³
^{99m} Tc MAA	2.8x10 ⁻³	4.0x10 ⁻³	5.0x10 ⁻³	4.0x10 ⁻³
^{99m} Tc MAG3	1.8x10 ⁻²	1.4x10 ⁻²	5.5x10 ⁻³	5.2x10 ⁻³
^{99m} Tc MDP	6.1x10 ⁻³	5.4x10 ⁻³	2.7x10 ⁻³	2.4x10 ⁻³
^{99m} Tc MIBI-rest	1.5x10 ⁻²	1.2x10 ⁻²	8.4x10 ⁻³	5.4x10 ⁻³
^{99m} Tc MIBI-stress	1.2x10 ⁻²	9.5x10 ⁻³	6.9x10 ⁻³	4.4x10 ⁻³
^{99m} Tc Pertechnetate	1.1x10 ⁻²	2.2x10 ⁻²	1.4x10 ⁻²	9.3x10 ⁻³
^{99m} Tc PYP	6.0x10 ⁻³	6.6x10 ⁻³	3.6x10 ⁻³	2.9x10 ⁻³
^{99m} Tc RBC-Heat Treated	1.7x10 ⁻³	1.6x10 ⁻³	2.1x10 ⁻³	2.2x10 ⁻³
^{99m} Tc RBC-in vitro	6.8x10 ⁻³	4.7x10 ⁻³	3.4x10 ⁻³	2.8x10 ⁻³
^{99m} Tc RBC-in vivo	6.4x10 ⁻³	4.3x10 ⁻³	3.3x10 ⁻³	2.7x10 ⁻³
^{99m} Tc Sulfur Colloid-normal	1.8x10 ⁻³	2.1x10 ⁻³	3.2x10 ⁻³	3.7x10 ⁻³
^{99m} Tc Sulfur Colloid-Liver Disease	3.2x10 ⁻³	2.5x10 ⁻³	2.8x10 ⁻³	2.8x10 ⁻³
^{99m} Tc Teboroxime	8.9x10 ⁻³	7.1x10 ⁻³	5.8x10 ⁻³	3.7x10 ⁻³
^{99m} Tc White Blood Cells	3.8x10 ⁻³	2.8x10 ⁻³	2.9x10 ⁻³	2.8x10 ⁻³
²⁰¹ Tl Chloride	9.7x10 ⁻²	5.8x10 ⁻²	4.7x10 ⁻²	2.7x10 ⁻²
¹²⁷ Xe, 5 minute rebreathing, 5 liter spirometer volume	4.3x10 ⁻⁴	2.4x10 ⁻⁴	1.9x10 ⁻⁴	1.5x10 ⁻⁴
¹²⁷ Xe, 5 minute rebreathing, 7.5 liter spirometer volume	2.3x10 ⁻⁴	1.3x10 ⁻⁴	1.0x10 ⁻⁴	8.4x10 ⁻⁵
¹²⁷ Xe, 5 minute rebreathing, 10 liter spirometer volume	2.3x10 ⁻⁴	1.4x10 ⁻⁴	1.1x10 ⁻⁴	9.2x10 ⁻⁵
¹³³ Xe, 5 minute rebreathing, 5 liter spirometer volume	4.1x10 ⁻⁴	4.8x10 ⁻⁵	3.5x10 ⁻⁵	2.6x10 ⁻⁵
¹³³ Xe, 5 minute rebreathing, 7.5 liter spirometer volume	2.2x10 ⁻⁴	2.6x10 ⁻⁵	1.9x10 ⁻⁵	1.5x10 ⁻⁵
¹³³ Xe, 5 minute rebreathing, 10 liter spirometer volume	2.5x10 ⁻⁴	2.9x10 ⁻⁵	2.1x10 ⁻⁵	1.6x10 ⁻⁵
¹³³ Xe, injection	4.9x10 ⁻⁶	1.0x10 ⁻⁶	1.4x10 ⁻⁶	1.6x10 ⁻⁶

*mGy/MBq x 3.7 ≡ rad/mCi.

†Stabin 2004.

Table 3-4. Fetal dose estimates from various nuclear medicine procedures (shading indicates maternal and fetal self dose contributions)
(from Russell et al. (1997b))

Radiopharmaceutical	Activity Administered MBq (mCi)	Fetal dose			
		Early mGy (rad)	3 Month mGy (rad)	6 Month mGy (rad)	9 Month mGy (rad)
⁵⁷ Co Vitamin B-12 Normal-Flushing	0.04 (0.001)	4.0x10 ⁻² (4.0x10 ⁻³)	2.7x10 ⁻² (2.7x10 ⁻³)	3.4x10 ⁻² (3.4x10 ⁻³)	3.5x10 ⁻² (3.5x10 ⁻³)
⁵⁷ Co Vitamin B-12 Normal-No Flushing	0.04 (0.001)	6.0x10 ⁻² (6.0x10 ⁻³)	4.0x10 ⁻² (4.0x10 ⁻³)	4.8x10 ⁻² (4.8x10 ⁻³)	5.2x10 ⁻² (5.2x10 ⁻³)
⁵⁷ Co Vitamin B-12 Pernicious Anemia-Flushing	0.04 (0.001)	8.4x10 ⁻³ (8.4x10 ⁻⁴)	6.8x10 ⁻³ (6.8x10 ⁻⁴)	6.8x10 ⁻³ (6.8x10 ⁻⁴)	6.0x10 ⁻³ (6.0x10 ⁻⁴)
⁵⁷ Co Vitamin B-12 Pernicious Anemia-No Flushing	0.04 (0.001)	1.1x10 ⁻² (1.1x10 ⁻³)	8.4x10 ⁻³ (8.4x10 ⁻⁴)	8.8x10 ⁻³ (8.8x10 ⁻⁴)	8.0x10 ⁻³ (8.0x10 ⁻⁴)
⁵⁸ Co Vitamin B-12 Normal-Flushing	0.03 (0.0008)	7.5x10 ⁻² (7.5x10 ⁻³)	5.7x10 ⁻² (5.7x10 ⁻³)	6.3x10 ⁻² (6.3x10 ⁻³)	6.3x10 ⁻² (6.3x10 ⁻³)
⁵⁸ Co Vitamin B-12 Normal-No Flushing	0.03 (0.0008)	1.1x10 ⁻¹ (1.1x10 ⁻²)	8.4x10 ⁻² (8.4x10 ⁻³)	9.3x10 ⁻² (9.3x10 ⁻³)	9.3x10 ⁻² (9.3x10 ⁻³)
⁵⁸ Co Vitamin B-12 Pernicious Anemia-Flushing	0.03 (0.0008)	2.5x10 ⁻² (2.5x10 ⁻³)	2.2x10 ⁻² (2.2x10 ⁻³)	1.9x10 ⁻² (1.9x10 ⁻³)	1.4x10 ⁻² (1.4x10 ⁻³)
⁵⁸ Co Vitamin B-12 Pernicious Anemia-No Flushing	0.03 (0.0008)	2.9x10 ⁻² (2.9x10 ⁻³)	2.6x10 ⁻² (2.6x10 ⁻³)	2.3x10 ⁻² (2.3x10 ⁻³)	1.8x10 ⁻² (1.8x10 ⁻³)
¹⁸ F FDG	370 (10)	8.1x10 ⁰ (8.1x10 ⁻¹)	8.1x10 ⁰ (8.1x10 ⁻¹)	6.3x10 ⁰ (6.3x10 ⁻¹)	6.3x10 ⁰ (6.3x10 ⁻¹)
⁶⁷ Ga Citrate	190 (5)	1.8x10 ¹ (1.8x10 ⁰)	3.8x10 ¹ (3.8x10 ⁰)	3.4x10 ¹ (3.4x10 ⁰)	2.5x10 ¹ (2.5x10 ⁰)
¹⁹⁷ Hg Chlormerodrin	4 (0.1)	4.4x10 ⁻² (4.4x10 ⁻³)	3.0x10 ⁻² (3.0x10 ⁻³)	2.7x10 ⁻² (2.7x10 ⁻³)	2.8x10 ⁻² (2.8x10 ⁻³)
¹²³ I Hippuran	75 (2)	2.3x10 ⁰ (2.3x10 ⁻¹)	1.8x10 ⁰ (1.8x10 ⁻¹)	6.3x10 ⁻¹ (6.3x10 ⁻²)	5.9x10 ⁻¹ (5.9x10 ⁻²)
¹²³ I IMP	200 (5.5)	3.8x10 ⁰ (3.8x10 ⁻¹)	2.2x10 ⁰ (2.2x10 ⁻¹)	1.4x10 ⁰ (1.4x10 ⁻¹)	1.2x10 ⁰ (1.2x10 ⁻¹)
¹²³ I MIBG	350 (9.5)	6.3x10 ⁰ (6.3x10 ⁻¹)	4.2x10 ⁰ (4.2x10 ⁻¹)	2.4x10 ⁰ (2.4x10 ⁻¹)	2.2x10 ⁰ (2.2x10 ⁻¹)
phaeochromocytoma	80	1.4x10 ⁰	9.6x10 ⁻¹	5.4x10 ⁻¹	5.0x10 ⁻¹
cecholamine tumor					

¹²³ I Sodium Iodide	(2)	(1.4x10 ⁻¹)	(9.6x10 ⁻²)	(5.4x10 ⁻²)	(5.0x10 ⁻²)
thyroid uptake study	30	6.0x10 ⁻¹	4.2x10 ⁻¹	3.3x10 ⁻¹	2.9x10 ⁻¹
thyroid imaging	(0.8)	(6.0x10 ⁻²)	(4.2x10 ⁻²)	(3.3x10 ⁻²)	(2.9x10 ⁻²)
	15	3.0x10 ⁻¹	2.1x10 ⁻¹	1.7x10 ⁻¹	1.4x10 ⁻¹
	(0.4)	(3.0x10 ⁻²)	(2.1x10 ⁻²)	(1.7x10 ⁻²)	(1.4x10 ⁻³)
¹²⁵ I HSA	2	5.0x10 ⁻¹	1.6x10 ⁻¹	7.6x10 ⁻²	5.2x10 ⁻²
	(0.05)	(5.0x10 ⁻²)	(1.6x10 ⁻²)	(7.6x10 ⁻³)	(5.2x10 ⁻³)
¹²⁵ I NaI	1	1.8x10 ⁻²	9.5x10 ⁻³	3.5x10 ⁻³	2.3x10 ⁻³
	(0.03)	(1.8x10 ⁻³)	(9.5x10 ⁻⁴)	(3.5x10 ⁻⁴)	(2.3x10 ⁻⁴)
¹³¹ I Hippuran					
renal function	1.3	8.3x10 ⁻²	6.5x10 ⁻²	2.5x10 ⁻²	2.3x10 ⁻²
	(0.035)	(8.3x10 ⁻³)	(6.5x10 ⁻³)	(2.5x10 ⁻³)	(2.3x10 ⁻³)
renal imaging	1.3	8.3x10 ⁻²	6.5x10 ⁻²	2.5x10 ⁻²	2.3x10 ⁻²
	(0.035)	(8.3x10 ⁻³)	(6.5x10 ⁻³)	(2.5x10 ⁻³)	(2.3x10 ⁻³)
¹³¹ I HSA	0.5	2.6x10 ⁻¹	9.0x10 ⁻²	8.0x10 ⁻²	6.5x10 ⁻²
	(0.013)	(2.6x10 ⁻²)	(9.0x10 ⁻³)	(8.0x10 ⁻³)	(6.5x10 ⁻³)
¹³¹ I MAA	55	3.7x10 ⁰	2.3x10 ⁰	2.2x10 ⁰	2.3x10 ⁰
	(1.5)	(3.7x10 ⁻¹)	(2.3x10 ⁻¹)	(2.2x10 ⁻¹)	(2.3x10 ⁻¹)
¹³¹ I MIBG	20	2.2x10 ⁰	1.1x10 ⁰	7.6x10 ⁻¹	7.0x10 ⁻¹
	(0.5)	(2.2x10 ⁻¹)	(1.1x10 ⁻¹)	(7.6x10 ⁻²)	(7.0x10 ⁻²)
¹³¹ I NaI (Diagnostic)					
thyroid uptake	0.55	4.0x10 ⁻²	3.7x10 ⁻²	1.3x10 ⁻¹	1.5x10 ⁻¹
	(0.015)	(4.0x10 ⁻³)	(3.7x10 ⁻³)	(1.3x10 ⁻²)	(1.5x10 ⁻²)
scintiscanning	4	2.9x10 ⁻¹	2.7x10 ⁻¹	9.2x10 ⁻¹	1.1x10 ⁰
	(0.11)	(2.9x10 ⁻²)	(2.7x10 ⁻²)	(9.2x10 ⁻²)	(1.1x10 ⁻¹)
localization of extra-thyroid metastases	40	2.9x10 ⁰	2.7x10 ⁰	9.2x10 ⁰	1.1x10 ¹
	(1.1)	(2.9x10 ⁻¹)	(2.7x10 ⁻¹)	(9.2x10 ⁻¹)	(1.1x10 ⁰)
¹³¹ I NaI (Therapeutic)					
hyperthyroidism	350	2.5x10 ¹	2.3x10 ¹	8.1x10 ¹	9.5x10 ¹
	(9.5)	(2.5x10 ⁰)	(2.3x10 ⁰)	(8.1x10 ⁰)	(9.5x10 ⁰)
ablation of normal thyroid tissue	1900	1.4x10 ²	1.3x10 ²	4.4x10 ²	5.1x10 ²
	(50)	(1.4x10 ¹)	(1.3x10 ¹)	(4.4x10 ¹)	(5.1x10 ¹)
¹³¹ I Rose Bengal	0.04	8.8x10 ⁻³	8.8x10 ⁻³	6.4x10 ⁻³	3.6x10 ⁻³
	(0.001)	(8.8x10 ⁻⁴)	(8.8x10 ⁻⁴)	(6.4x10 ⁻⁴)	(3.6x10 ⁻⁴)
¹¹¹ In DTPA	20	1.3x10 ⁰	9.6x10 ⁻¹	4.0x10 ⁻¹	3.6x10 ⁻¹
	(0.5)	(1.3x10 ⁻¹)	(9.6x10 ⁻²)	(4.0x10 ⁻²)	(3.6x10 ⁻²)
¹¹¹ In Pentetate					
planar imaging	110	9.0x10 ⁰	6.6x10 ⁰	3.8x10 ⁰	3.4x10 ⁰
	(3)	(9.0x10 ⁻¹)	(6.6x10 ⁻¹)	(3.8x10 ⁻¹)	(3.4x10 ⁻¹)
SPECT imaging	230	1.9x10 ¹	1.4x10 ¹	8.0x10 ⁰	7.0x10 ⁰
	(6)	(1.9x10 ⁰)	(1.4x10 ⁰)	(8.0x10 ⁻¹)	(7.0x10 ⁻¹)
¹¹¹ In Platelets	10	1.7x10 ⁰	1x10 ⁰	9.9x10 ⁻¹	8.9x10 ⁻¹
	(0.25)	(1.7x10 ⁻¹)	(1.1x10 ⁻¹)	(9.9x10 ⁻²)	(8.9x10 ⁻²)
¹¹¹ In White Blood Cell	20	2.6x10 ⁰	1.9x10 ⁰	1.9x10 ⁰	1.9x10 ⁰

^{81m}Kr Gas	(0.5) 600	(2.6x10 ⁻¹) 1.1x10 ⁻⁴	(1.9x10 ⁻¹) 1.0x10 ⁻⁴	(1.9x10 ⁻¹) 1.6x10 ⁻⁴	(1.9x10 ⁻¹) 2.0x10 ⁻⁴
^{99m}Tc Disofenin	(15) 350	(1.1x10 ⁻⁵) 6.0x10 ⁰	(1.0x10 ⁻⁵) 5.2x10 ⁰	(1.6x10 ⁻⁵) 4.2x10 ⁰	(2.0x10 ⁻⁵) 2.3x10 ⁰
^{99m}Tc DMSA	(9.5) 220	(6.0x10 ⁻¹) 1.1x10 ⁰	(5.2x10 ⁻¹) 1.0x10 ⁰	(4.2x10 ⁻¹) 8.8x10 ⁻¹	(2.3x10 ⁻¹) 7.5x10 ⁻¹
^{99m}Tc DTPA	(6)	(1.1x10 ⁻¹)	(1.0x10 ⁻¹)	(8.8x10 ⁻²)	(7.5x10 ⁻²)
kidney imaging & glomerular filtration	750	9.0x10 ⁰	6.5x10 ⁰	3.1x10 ⁰	3.5x10 ⁰
brain imaging & renal perfusion	(20) 750	(9.0x10 ⁻¹) 9.0x10 ⁰	(6.5x10 ⁻¹) 6.5x10 ⁰	(3.1x10 ⁻¹) 3.1x10 ⁰	(3.5x10 ⁻¹) 3.5x10 ⁰
1st pass	(20) 350	(9.0x10 ⁻¹) 4.2x10 ⁰	(6.5x10 ⁻¹) 3.0x10 ⁰	(3.1x10 ⁻¹) 1.4x10 ⁰	(3.5x10 ⁻¹) 1.6x10 ⁰
gastric reflux	(9.5) 10	(4.2x10 ⁻¹) 1.2x10 ⁻¹	(3.0x10 ⁻¹) 8.7x10 ⁻²	(1.4x10 ⁻¹) 4.1x10 ⁻²	(1.6x10 ⁻¹) 4.7x10 ⁻²
hypertension	(0.27) 800	(1.2x10 ⁻²) 9.6x10 ⁰	(8.7x10 ⁻³) 7.0x10 ⁰	(4.1x10 ⁻³) 3.3x10 ⁰	(4.7x10 ⁻³) 3.8x10 ⁰
residual urine determination	(22) 350	(9.6x10 ⁻¹) 4.2x10 ⁰	(7.0x10 ⁻¹) 3.0x10 ⁰	(3.3x10 ⁻¹) 1.4x10 ⁰	(3.8x10 ⁻¹) 1.6x10 ⁰
^{99m}Tc DTPA Aerosol	(9.5) 40	(4.2x10 ⁻¹) 2.3x10 ⁻¹	(3.0x10 ⁻¹) 1.7x10 ⁻¹	(1.4x10 ⁻¹) 9.2x10 ⁻²	(1.6x10 ⁻¹) 1.2x10 ⁻¹
^{99m}Tc Glucoheptonate	(1.1)	(2.3x10 ⁻²)	(1.7x10 ⁻²)	(9.2x10 ⁻³)	(1.2x10 ⁻²)
renal imaging	750	9.0x10 ⁰	8.2x10 ⁰	4.0x10 ⁰	3.4x10 ⁰
brain imaging	(20) 750	(9.0x10 ⁻¹) 9.0x10 ⁰	(8.2x10 ⁻¹) 8.2x10 ⁰	(4.0x10 ⁻¹) 4.0x10 ⁰	(3.4x10 ⁻¹) 3.4x10 ⁰
^{99m}Tc HDP	(20) 750	(9.0x10 ⁻¹) 3.9x10 ⁰	(8.2x10 ⁻¹) 4.1x10 ⁰	(4.0x10 ⁻¹) 2.3x10 ⁰	(3.4x10 ⁻¹) 1.9x10 ⁰
^{99m}Tc HMPAO	(20)	(3.9x10 ⁻¹)	(4.0x10 ⁻¹)	(2.3x10 ⁻¹)	(1.9x10 ⁻¹)
^{99m}Tc Human Serum Albumin	750 (20) 200	6.5x10 ⁰ (6.5x10 ⁻¹) 1.0x10 ⁰	5.0x10 ⁰ (5.0x10 ⁻¹) 6.0x10 ⁻¹	3.6x10 ⁰ (3.6x10 ⁻¹) 5.2x10 ⁻¹	2.7x10 ⁰ (2.7x10 ⁻¹) 4.4x10 ⁻¹
^{99m}Tc MAA	(5.5)	(1.0x10 ⁻¹)	(6.0x10 ⁻²)	(5.2x10 ⁻²)	(4.4x10 ⁻²)
hepatic artery perfusion	150	4.2x10 ⁻¹	6.0x10 ⁻¹	7.5x10 ⁻¹	6.0x10 ⁻¹
lung imaging	(4) 200	(4.2x10 ⁻²) 5.6x10 ⁻¹	(6.0x10 ⁻²) 8.0x10 ⁻¹	(7.5x10 ⁻²) 1.0x10 ⁰	(6.0x10 ⁻²) 8.0x10 ⁻¹
isotopic venography	(5.5) 220	(5.6x10 ⁻²) 6.2x10 ⁻¹	(8.0x10 ⁻²) 8.8x10 ⁻¹	(1.0x10 ⁻¹) 1.1x10 ⁰	(8.0x10 ⁻²) 8.0x10 ⁻¹
LeVeen shunt patency	(6) 110	(6.2x10 ⁻²) 3.1x10 ⁻¹	(8.8x10 ⁻²) 4.4x10 ⁻¹	(1.1x10 ⁻¹) 5.5x10 ⁻¹	(8.0x10 ⁻²) 4.4x10 ⁻¹
^{99m}Tc MAG3	(3)	(3.1x10 ⁻²)	(4.4x10 ⁻²)	(5.5x10 ⁻²)	(4.4x10 ⁻²)
^{99m}Tc MAG3	750 (20)	1.4x10 ¹ (1.4x10 ⁰)	1.0x10 ¹ (1.0x10 ⁰)	4.1x10 ⁰ (4.1x10 ⁻¹)	3.9x10 ⁰ (3.9x10 ⁻¹)
^{99m}Tc MDP	750	4.6x10 ⁰	4.0x10 ⁰	2.0x10 ⁰	1.8x10 ⁰

^{99m} Tc MIBI-rest	(20)	(4.6x10 ⁻¹)	(4.0x10 ⁻¹)	(2.0x10 ⁻¹)	(1.8x10 ⁻¹)
	1100	1.7x10 ¹	1.3x10 ¹	9.2x10 ⁰	5.9x10 ⁰
	(30)	(1.7x10 ⁰)	(1.3x10 ⁰)	(9.2x10 ⁻¹)	(5.9x10 ⁻¹)
	1100	1.3x10 ¹	1.0x10 ¹	7.6x10 ⁰	4.8x10 ⁰
^{99m} Tc MIBI-stress	(30)	(1.3x10 ⁰)	(1.0x10 ⁰)	(7.6x10 ⁻¹)	(4.8x10 ⁻¹)
^{99m} Tc Pertechnetate	1100	1.2x10 ¹	2.4x10 ¹	1.5x10 ¹	1.0x10 ¹
	(30)	(1.2x10 ⁰)	(2.4x10 ⁰)	(1.5x10 ⁰)	(1.0x10 ⁰)
	400	4.4x10 ⁰	8.8x10 ⁰	5.6x10 ⁰	3.7x10 ⁰
	(11)	(4.4x10 ⁻¹)	(8.8x10 ⁻¹)	(5.6x10 ⁻¹)	(3.7x10 ⁻¹)
	200	2.2x10 ⁰	4.4x10 ⁰	2.8x10 ⁰	1.9x10 ⁰
	(5.5)	(2.2x10 ⁻¹)	(4.4x10 ⁻¹)	(2.8x10 ⁻¹)	(1.9x10 ⁻¹)
	110	1.1x10 ⁰	2.4x10 ⁰	1.5x10 ⁰	1.0x10 ⁰
	(3)	(1.1x10 ⁻¹)	(2.4x10 ⁻¹)	(1.5x10 ⁻¹)	(1.0x10 ⁻¹)
	1100	1.1x10 ¹	2.4x10 ¹	1.4x10 ¹	1.0x10 ¹
	(30)	(1.1x10 ⁰)	(2.4x10 ⁰)	(1.4x10 ⁰)	(1.0x10 ⁰)
	550	6.0x10 ⁰	1.2x10 ¹	7.7x10 ⁰	5.1x10 ⁰
	(15)	(6.0x10 ⁻¹)	(1.2x10 ⁰)	(7.7x10 ⁻¹)	(5.1x10 ⁻¹)
	550	6.0x10 ⁰	1.2x10 ¹	7.7x10 ⁰	5.1x10 ⁰
	(15)	(6.0x10 ⁻¹)	(1.2x10 ⁰)	(7.7x10 ⁻¹)	(5.1x10 ⁻¹)
^{99m} Tc PYP	550	3.3x10 ⁰	3.6x10 ⁰	2.0x10 ⁰	1.6x10 ⁰
	(15)	(3.3x10 ⁻¹)	(3.6x10 ⁻¹)	(2.0x10 ⁻¹)	(1.6x10 ⁻¹)
	700	4.2x10 ⁰	4.6x10 ⁰	2.5x10 ⁰	2.0x10 ⁰
	(19)	(4.2x10 ⁻¹)	(4.6x10 ⁻¹)	(2.5x10 ⁻¹)	(2.0x10 ⁻¹)
^{99m} Tc RBC - in vitro labeling	930	6.3x10 ⁰	4.4x10 ⁰	3.2x10 ⁰	2.6x10 ⁰
	(25)	(6.3x10 ⁻¹)	(4.4x10 ⁻¹)	(3.2x10 ⁻¹)	(2.6x10 ⁻¹)
^{99m} Tc RBC - in vivo labeling rest	550	3.5x10 ⁰	2.4x10 ⁰	1.8x10 ⁰	1.5x10 ⁰
	(15)	(3.5x10 ⁻¹)	(2.4x10 ⁻¹)	(1.8x10 ⁻¹)	(1.5x10 ⁻¹)
exercise	930	6.0x10 ⁰	4.0x10 ⁰	3.1x10 ⁰	2.5x10 ⁰
	(25)	(6.0x10 ⁻¹)	(4.0x10 ⁻¹)	(3.1x10 ⁻¹)	(2.5x10 ⁻¹)
lower GI bleeding	930	6.0x10 ⁰	4.0x10 ⁰	3.1x10 ⁰	2.5x10 ⁰
	(25)	(6.0x10 ⁻¹)	(4.0x10 ⁻¹)	(3.1x10 ⁻¹)	(2.5x10 ⁻¹)
^{99m} Tc Sulfur Colloid-normal liver-spleen imaging	300	5.4x10 ⁻¹	6.3x10 ⁻¹	9.6x10 ⁻¹	1.1x10 ⁰
	(8)	(5.4x10 ⁻²)	(6.3x10 ⁻²)	(9.6x10 ⁻²)	(1.1x10 ⁻¹)
bone marrow imaging	450	8.1x10 ⁻¹	9.5x10 ⁻¹	1.4x10 ⁰	1.7x10 ⁰
	(12)	(8.1x10 ⁻²)	(9.5x10 ⁻²)	(1.4x10 ⁻¹)	(1.7x10 ⁻¹)
pulmonary aspiration	20	3.6x10 ⁻²	4.2x10 ⁻²	6.4x10 ⁻²	7.4x10 ⁻²
	(0.5)	(3.6x10 ⁻³)	(4.2x10 ⁻³)	(6.4x10 ⁻³)	(7.4x10 ⁻³)
LeVein shunt patency	110	2.0x10 ⁻¹	2.3x10 ⁻¹	3.5x10 ⁻¹	4.1x10 ⁻¹
	(3)	(2.0x10 ⁻²)	(2.3x10 ⁻²)	(3.5x10 ⁻²)	(4.1x10 ⁻²)
^{99m} Tc White Blood Cells	200	7.6x10 ⁻¹	5.6x10 ⁻¹	5.8x10 ⁻¹	5.6x10 ⁻¹