1. Executive Summary

1.1 Background and Purpose

This Report updates and expands the National Council on Radiation Protection and Measurements (NCRP) Report No. 54, *Medical Radiation Exposure of Pregnant and Potentially Pregnant Women* (NCRP, 1977a). Scientific knowledge has increased and public concerns have changed in the nearly 36 y since NCRP (1977a) was published. The scope of this Report covers both ionizing radiation and nonionizing sources [i.e., magnetic-resonance imaging (MRI), ultrasound imaging, and other radiofrequency (RF) fields]. For ionizing radiation, the Report considers preconception and prenatal exposure, and exposure of the nursing infant. The ionizing radiation sources discussed consist predominantly of low linear energy transfer (LET) radiation. For nonionizing sources, the Report focuses on prenatal exposure, with a limited amount of information on childhood and adult exposure.

1.2 Ionizing Radiation Exposures of Reproductive Relevance

Ionizing radiation associated with medical procedures is typically the radiation exposure that causes the greatest concern and anxiety to pregnant women. However, if imaging examinations are medically indicated and performed with proper equipment and careful technique, then the potential immediate benefit to the health of the patient and the embryo or fetus will outweigh the potential future radiation risk. Most diagnostic medical imaging procedures in radiography, computed tomography (CT), conventional fluoroscopy, and nuclear medicine subject the embryo or fetus to absorbed doses of 10 mGy or less. Doses delivered to the embryo or fetus during fluoroscopically-guided interventional procedures and during the course of radiation therapy may be higher. Particularly for radiation therapy, the dose to the embryo or fetus should be evaluated by a qualified expert.

1.3 Preconception Ionizing Radiation Risks

There is no convincing direct evidence of germline mutation manifest as heritable disease in the offspring of humans and attributable to ionizing radiation, yet radiation clearly induces mutations
in microbes and somatic cells of rodents and humans, and transgen-
erational effects in irradiated drosophila and mice are established. 
It would be imprudent to ignore the possibility of human germ-cell 
mutation, especially since progress in human genetics and genom-
ics promises quantum improvements in being able to address the 
issue in the future.

The inheritance of mutations is a process that, in theory, has 
both a background component that is intrinsic in an individual and 
an induced component that results from environmental exposures 
such as ionizing radiation. A very small but undefined fraction of 
hereditary human disease is attributable to the environmental 
agents with mutagenic potential. In the absence of adequate human 
data, modeling and extrapolation have guided radiation protection.

Genetic risk is generally estimated using three components:

- doubling dose for radiation-induced germ-cell mutations in 
mice;
- background rate of sporadic genetic disease in humans; and
- population-genetics theory.

One additional consideration is that some deleterious muta-
tions (spontaneous or as a result of preconception radiation expo-
sure) would not be expressed as effects in an offspring because they 
are lethal to the developing ova (eggs) or sperm or to the developing 
embryo because of defective ova or sperm, a consideration that has 
been described as biological filtration.

There is little to no convincing or consistent evidence among 
the offspring of childhood cancer survivors, atomic-bomb survivors, 
environmentally-exposed populations, or occupationall-exposed 
workers for an excess of cytogenetic syndromes, single-gene disor-
ders, malformations, stillbirths, neonatal deaths, cancer, or cytoge-
netic markers that would indicate an increase of heritable genetic 
mutations in the exposed parents.

1.4 Pregnancy Risks from Ionizing Radiation

All pregnant women are faced with a baseline risk to the embryo 
and fetus for reproductive and developmental problems. The back-
ground rate for major congenital malformations is ~3 % (i.e., in the 
absence of radiation exposure about 3 of every 100 children born 
have a recognizable major birth defect). Minor malformations that 
are minimally disabling occur in an additional ~4 % of births. 
Pregnancy loss (spontaneous abortion, miscarriage) in women who 
know they are pregnant occurs in 15 % of pregnancies with a wide 
standard deviation.
Doses to the embryo estimated to be in the range of 0.15 to 0.2 Gy during the preimplantation and presomite stages may increase the risk of embryonic loss. However, an increased risk of congenital malformations or growth retardation has not been observed in the surviving embryos. These results are primarily derived from mammalian animal studies and are referred to as the “all-or-none phenomenon.”

The potential tissue reactions of ionizing radiation (previously referred to as deterministic effects) are congenital malformations, mental retardation, decreased intelligence quotient (IQ), microcephaly, neurobehavioral effects, convulsive disorders, growth retardation (height and weight), and embryonic and fetal death (miscarriage, stillbirth). Such effects are generally attributed to the killing of cells or serious disruption of cellular function during important stages of embryonic or fetal development. All these effects are consistent with having a threshold dose below which there is no increased risk. The data on IQ loss are somewhat difficult to interpret but even assuming that there might not be a true dose threshold, any IQ effects at low doses would be so small as to be undetectable and therefore not of practical or clinical significance. Doses to the embryo or fetus <0.1 Gy have not been found to increase the risk of tissue reactions in humans, including severe mental retardation, at any stage of pregnancy. Based on animal studies, the no-adverse-effect level (dose to the embryo or fetus) in humans is estimated at 0.2 Gy for anatomical congenital malformations during a very short period during early organogenesis, and is higher for most other tissue reactions.

Doses to the embryo or fetus due to radiation exposure to the maternal chest, extremities, neck and head from diagnostic x-ray procedures do not exceed 0.1 Gy and are thus less than the no-adverse-effect level for any of the previously mentioned tissue reactions. Doses to the embryo or fetus due to radionuclides used in diagnostic nuclear medicine and exposures during x-ray procedures of the maternal abdomen that do not exceed 0.1 Gy also do not increase the risk of tissue reactions.

The risk of cancer in offspring that have been exposed to diagnostic x-ray procedures while in utero has been debated for 55 y. High doses to the embryo or fetus (e.g., >0.5 Gy) increase the risk of cancer. Most pregnant women exposed to x-ray procedures and other forms of ionizing radiation today receive doses to the embryo or fetus <0.1 Gy. The risk of cancer in offspring exposed in utero at a low dose such as <0.1 Gy is controversial and has not been fully resolved. A fuller discussion of the range of opinion on this cancer risk can be found in Section 5.2.6 and the conclusions in Section 10.1.
Nevertheless, diagnostic imaging procedures utilizing ionizing radiation that are clinically indicated for the pregnant patient should be performed because the clinical benefits outweigh the potential oncogenic risks. However, when it has been determined that the procedure is necessary, it should be tailored to effectively manage the dose to the embryo or fetus (i.e., use only the least amount of radiation necessary to achieve the clinical purpose).

Table 1.1 summarizes for easy reference the health effects from ionizing radiation exposure of the embryo or fetus during various gestational stages of pregnancy.

### 1.5 Ionizing Radiation Risk to the Nursing Infant

If the mother has received a radiopharmaceutical, the nursing infant may be exposed, either as a result of transfer of the material to the infant by the mother's milk or by exposure to radiation from the mother's body. For diagnostic radiopharmaceuticals, recommended breast-feeding interruption intervals are provided. The most current of these are from the International Commission on Radiological Protection (ICRP, 2008). If the recommendations are followed, the effective dose that would be received by most infants would be far below 1 mSv. Iodine-131 therapy is a special case and should not be administered unless breast-feeding is terminated. To minimize the infant's dose from exposure to the mother's body, the mother should be advised to hold the infant as little as possible during the immediate postadministration period when doses from $^{131}$I would be highest. If the mother is receiving brachytherapy, the infant could be exposed to a significant amount of radiation unless the amount of time that the infant is in close contact to the mother during treatment is limited.

When there is evidence that the mother has inhaled or ingested radiiodine from an accident or other incident, typically $^{131}$I, lactating women should be administered potassium iodide for both their protection as well as to potentially reduce the radioiodine content of their breast milk (FDA, 2001). If the radioiodine burden in the mother is significant or if repeated doses to the mother of potassium iodide are required, the infant should be evaluated for hypothyroidism and discontinuation of breast-feeding may be warranted. In such rare instances, breast-feeding should be replaced by packaged feedings which are known to be free of contamination. Intake of $^{131}$I by the infant from breast-feeding can be estimated using ICRP (2004).
<table>
<thead>
<tr>
<th>Human Gestational Stage (weeks)</th>
<th>Comments&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heritable Disease</td>
<td></td>
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<tr>
<td>1st and 2nd weeks prior to conception (begins on the first day of the last menstrual period)</td>
<td>Irradiation of ova or sperm prior to conception. The mother has not yet ovulated. There is no convincing evidence of excess heritable disease in the offspring. [Section 4]</td>
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<tr>
<td>Embryonic or Fetal Loss, Malformations, Growth Retardation&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
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<tr>
<td>3rd and 4th weeks of gestation (1st and 2nd weeks postconception)</td>
<td>Minimum human acute lethal dose for the embryo (derived from animal studies) is estimated to be in the range 0.15 to 0.2 Gy. This is the most vulnerable period for the increased risk of radiation-induced embryonic death. The risk of a viable malformed fetus at term is not increased (all-or-none period). [Section 5.1.5]</td>
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<tr>
<td>5th to 7th weeks of gestation (3rd to 5th weeks postconception)</td>
<td>Minimum human acute lethal dose for the embryo (derived from animal studies) is estimated to be in the range 0.25 to 0.5 Gy. The no-adverse-effect level for the induction of birth defects increases during this period and doses &gt;0.5 Gy are necessary to induce major malformations at the end of this period. The induced growth retardation during this period is not as severe as during the 8th to 15th weeks of gestation, and the embryos have a greater capacity to recover from the in utero growth retardation effect. The no-adverse-effect level is in the range of 0.2 to 0.5 Gy. [Sections 5 and 5.1.7]</td>
</tr>
<tr>
<td>8th to 15th weeks of gestation (6th to 13th weeks postconception)</td>
<td>Minimum human acute lethal dose for the fetus (derived from animal studies) is estimated to be &gt;1 Gy. The most vulnerable period for irreversible whole-body growth retardation. The no-adverse-effect level is in the range of 0.25 to 0.5 Gy. [Sections 5 and 5.1.7]</td>
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### Table 1.1—(continued)

<table>
<thead>
<tr>
<th>Human Gestational Stage (weeks)</th>
<th>Comments&lt;sup&gt;a&lt;/sup&gt;</th>
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<tbody>
<tr>
<td>16th to 25th weeks of gestation</td>
<td>Minimum human acute lethal dose for the fetus (derived from animal studies) is estimated to be ~2 Gy. Growth retardation can be produced, although the effects are not as severe as occurs from the 8th to 15th weeks of gestation. Since all the organs have been formed, the important risk of irradiation is cell depletion in the brain and organs producing ova and sperm. [Section 5.1.7]</td>
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<tr>
<td>(14th to 23rd weeks postconception)</td>
<td></td>
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<tr>
<td>26th week to term delivery</td>
<td>During the last 15 weeks of pregnancy the doses that have deleterious effects on growth, mortality, the central nervous system, and the gonads would have to be increased. It is difficult to utilize animal studies to determine the no-adverse-effect level for various deleterious effects since there is marked discordance in human brain development and the rodent models that are used in this type of research. [Section 5.1.7]</td>
</tr>
<tr>
<td>(24th week postconception to term)</td>
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</table>

**Mental Retardation**<sup>b</sup>

<table>
<thead>
<tr>
<th>Human Gestational Stage (weeks)</th>
<th>Comments&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>10th to 27th weeks of gestation</td>
<td>Severe mental retardation observed at doses &gt;0.5 Gy (lower 95% CI value of ~0.3 Gy). Decreases in intelligent quotient also observed for this period. Severe mental retardation was not observed prior to the 8th week postconception or after the 25th week postconception. [Section 5.2.1.1]</td>
</tr>
<tr>
<td>(8th to 25th weeks postconception)</td>
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</table>

**Oncogenic Effects (cancer)**

<table>
<thead>
<tr>
<th>Human Gestational Stage (weeks)</th>
<th>Comments&lt;sup&gt;a&lt;/sup&gt;</th>
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<tr>
<td>Throughout gestation</td>
<td>The lifetime risk of oncogenic effects following \textit{in utero} irradiation appears to be lower than that following irradiation during childhood. There is not data available that informs on which stages of pregnancy may be the most vulnerable to the oncogenic effects of irradiation. [Section 5.2.6]</td>
</tr>
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<sup>a</sup>Extended discussions of the health effects are found in the sections indicated.<br>
<sup>b</sup>There is no evidence of increased risks of these effects with doses to the embryo or fetus <0.1 Gy.<br>
<sup>c</sup>All doses refer to the dose to the embryo or fetus and are for low-LET radiation.
1.6 Mitigation of Ionizing Radiation Risk for Pregnant or Potentially-Pregnant Women

Prior to any medical ionizing radiation exposure, it is important to assess if the woman is pregnant, or if there is the possibility that she may be pregnant. The conventional methods of pregnancy assessment range from verbal communication to a highly-sensitive biochemical assay of human chorionic gonadotropin produced by the developing placenta. Nevertheless, a woman should be considered potentially pregnant if she thinks she may be pregnant or:

- is between 12 and 55 y of age (with no history of menopause), younger than 12 y of age and has started menstrual cycles, or older than 55 y of age without a history of menopause;
- has no reliable history or documented condition which results in sterility; and
- has not had a menstrual period beginning within the last three to four weeks.

Strategies for managing the dose to a pregnant woman and reducing the radiation risk to the embryo and fetus should be employed for all medical procedures involving ionizing radiation (diagnostic imaging procedures, interventional procedures, and radiation therapy). However, any adjustments should not be made at the expense of obtaining the necessary diagnostic information, compromising treatment, or affecting maternal health. The use of radiation therapy should be avoided for pregnant woman diagnosed with cancer, whenever possible, without jeopardizing the woman's life. However, targeted radiation therapy to an extremity, or the head, neck, chest or breast, may not result in a dose to the embryo or fetus that would increase the reproductive or developmental risks of the pregnancy. The use of alternative treatment such as surgery, chemotherapy or both (after consultation with the medical oncologist), should be considered as well as postponing radiation therapy until after delivery. The possibility of adverse outcomes associated with other treatment modalities should also be considered. The risk of teratogenicity from certain chemotherapy agents, for example, has been reported to be as high as 10 to 25 % in the first trimester. However there has been no evidence of increased risk of teratogenesis during the second and third trimesters, although there have been reports of higher rates of developmental effects (e.g., stillbirth and low birth weight).

Formal declaration of a pregnancy by a pregnant worker permits supervisors, if necessary, to take steps to control occupational exposure to radiation to less than that normally received. Mitigating unintentional exposures from involvement with accidents or
malicious use of radioactive materials is largely an after-the-fact process heavily dependent on the dose assessment and specific circumstances.

1.7 Risks to the Embryo or Fetus During Magnetic-Resonance Imaging

During magnetic-resonance imaging (MRI), the embryo or fetus is exposed to magnetic and electromagnetic fields from three sources:

- RF fields from the RF transmitter coil;
- time-varying magnetic field gradients with field changes on the order of 10 T s⁻¹; and
- the static magnetic field of the MRI system.

The main concern regarding the first source, RF electromagnetic fields, is direct heating of tissue. Excessive heating for prolonged time periods can overwhelm the thermoregulatory capacity of the body resulting in a variety of potential adverse health effects. Of special concern here is that sustained temperature elevation in the embryo or fetus may be teratogenic. Recommendations to minimize the RF exposure risk to the embryo or fetus include:

- avoid scanning the embryo or fetus at exposure parameters above the normal mode (Section 8.1.2);
- if the embryo or fetus or maternal abdomen are not the target organs of interest, then the embryo or fetus should be kept out of the transmit field of the RF coil if possible;
- particular care is necessary when scanning fetuses with poor placental function; and
- particular care is necessary when scanning pregnant women with conditions leading to impaired thermoregulation.

With regard to time-varying magnetic fields, current U.S. Food and Drug Administration guidelines (FDA, 2003) classify these fields as a significant risk when they are sufficient to produce severe discomfort or painful nerve stimulation. There is no evidence of harm to patients from the static field in the more than 300 million clinical MRI studies performed since the early 1980s. However, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) has concluded that the current upper limit for whole-body static magnetic field strength during normal clinical MRI examinations should be 4 T (ICNIRP, 2009a).

An American College of Radiology (ACR) expert panel (Kanal et al., 2007) does not believe that current data have conclusively
documented any deleterious effects of MRI exposure on the developing embryo or fetus. The panel concludes therefore that “no special consideration is recommended for the first, versus any other, trimester in pregnancy.” However, the panel recommends that the following considerations be documented in the radiology report or the patient’s medical record:

- information requested from the MRI study cannot be acquired \textit{via} other nonionizing modalities (e.g., ultrasonography);
- data are needed to potentially affect the care of the patient or the embryo or fetus during the pregnancy; and
- the referring physician does not feel it is prudent to wait until the patient is no longer pregnant to obtain these data.

Contrast agents should not be routinely administered for MRI examinations in pregnant patients. Although the risk to the fetus following administration of gadolinium-based MRI contrast agents has not been determined, the decision to administer a gadolinium-based MRI contrast agent to a pregnant patient should be accompanied by a well documented and thoughtful risk-benefit analysis for the fetus and mother.

1.8 Risks to the Embryo or Fetus from Other Radiofrequency Sources

There is increasing exposure to other sources of electromagnetic radiation in the radiofrequency (RF) range from television and radio broadcast towers as well as from new wireless communication and information technologies. In addition, exposure to millimeter wave and terahertz sources is expected to increase as new communication, airport screening, scanning, and imaging technologies are developed. The only accepted mechanism for adverse health effects due to an interaction of electromagnetic radiation in the RF and terahertz range with biological tissue (with the exception of neurostimulation below ~5 MHz) is the generation of heat. In the range of wireless communication and information technologies, the most recent revision of the Institute of Electrical and Electronics Engineers (IEEE) C95.1 standard (IEEE, 2005) allows for a rate of absorbed RF energy in members of the general public (including those that are pregnant) equal to 0.08 W kg\textsuperscript{-1} averaged over the entire body, or a rate of 2 W kg\textsuperscript{-1} averaged over a local tissue mass of 10 g. It should be noted that these recommended limits do not apply to medical use such as diathermy.

While many experimental and epidemiological studies have failed to demonstrate any consistent or convincing evidence of
adverse health effects from low-level (nonthermal)\textsuperscript{1} RF exposure, some associations have been reported in the scientific literature and reviewed by scientific working groups. In particular, based primarily on an international case-control study of adult cell-phone users by the INTERPHONE Study Group (ISG, 2010), the International Agency for Research on Cancer Working Group classified RF energy as a “possible human carcinogen” (IARC, 2013). In assigning this classification, IARC (2013) noted that while a positive association for increased risk of glioma (a rare form of brain cancer) at the highest exposure levels had been observed, chance, bias or confounding could not be ruled out as the cause for this association with reasonable confidence. Also, it should be noted that the study mentioned was not for \textit{in utero} exposure. Subsequent to the ISG (2010) study and IARC (2013) classification, additional studies and evaluations provided no support for a causal association between RF exposure from cell phones and risk of brain cancer. In the absence of a causal connection between RF exposure and various adverse health endpoints, the current consensus regarding long-term exposure at nonthermal levels is that there are no established adverse health effects of RF energy that are not associated with excessive heating.

\textbf{1.9 Risks to the Embryo or Fetus from Ultrasound Imaging}

Diagnostic ultrasound has been in use for over 50 y in obstetrics and gynecology. Based on the epidemiological evidence to date, there is little to no convincing evidence to support a causal relationship with any adverse effect including: low birth weight, delayed speech, dyslexia, nonright-handedness, and decreased intellectual performance. Nearly all epidemiological studies published to date are based on information obtained with ultrasound machines manufactured prior to 1992. In 1992 the acoustic output of ultrasound systems was allowed to be increased nearly eightfold for fetal use. Newer higher power technologies and their applications have been introduced over the years and thus continued vigilance in monitoring for possible fetal harm is warranted.

Nonthermal effects of ultrasound are not as well understood as thermal effects. Nonthermal effects include acoustic radiation force, acoustic streaming, and acoustic cavitation. Prior to the first

\textsuperscript{1}The term \textit{nonthermal} is widely used in the literature to refer to low-level exposures that result in deposition of energy ultimately deposited as heat that is well within the body’s thermoregulatory control thus avoiding a core temperature increase (IEEE, 2005).
breath of the newborn infant, however, there is a complete absence of air bubbles in the fetus and cavitation is not a concern. No adverse mechanical effects are known to occur in the fetus from diagnostic ultrasound examinations.

Presently there are several areas of importance pertaining to diagnostic ultrasound examinations performed during pregnancy. These are the use of Doppler in the first trimester, the use of contrast agents, and keepsake fetal imaging. The use of spectral Doppler ultrasound during the first trimester is currently considered a valuable diagnostic aid for some congenital abnormalities. The procedure requires considerable skill, and subjects the fetus to extended periods of relatively-high ultrasound exposure levels. Because of the potential for risk of adverse effects, it has been recommended that the use of Doppler ultrasound in the first trimester should only be employed when there is a clear benefit-risk advantage. The use of contrast agents in fetal imaging has been limited, and is usually advised against because of an increased possibility of a nonthermal adverse event. Imaging the fetus for keepsake purposes is not desirable and FDA has advised against exposing the fetus to ultrasound except for direct medical benefit to the patient or fetus, and when performed by trained health professionals.

The thermal index (TI) and the mechanical index (MI) are ultrasound safety indices that have been developed to provide ultrasound users with a continuously updated on-screen guide to the relative level of risk of an ultrasound examination while it is being performed. Values $\leq 1$ indicate minimal risk and that an ultrasound examination need not be withheld because of a safety concern. A value $>1$ indicates some risk and that the benefit-risk ratio should be evaluated in deciding whether to do or continue the examination. The higher acoustic outputs of Doppler-mode examinations are also reflected in higher TI values, where values as high as six may be seen and greater caution is needed. In general the TI and MI indices should be maintained as low as feasible while obtaining the required diagnostic information.

### 1.10 Communicating Benefits and Risks

Women exposed to radiation during pregnancy and members of their families often seek counseling about the associated radiation exposure and present with various levels of anxiety. Similarly, radiation exposure to future fathers or mothers before conception can be a concern. In such circumstances it is important that the counselor be well versed in the potential adverse consequences associated with various levels of radiation exposure, and the chances of the
effects occurring, so as not to inadvertently raise concern. Unfortu-
nately, many professionals who provide care for pregnant patients
have limited knowledge of the biological effects of ionizing radiation
and exposure from nonionizing modalities in pregnancy. Conse-
quently, more harm may be done by inadequate counseling after an
exposure than that possible by the radiation exposure itself. The
circumstances surrounding an inadvertent exposure of a patient or
pregnant woman may also carry a burden that inaccurate counsel-
ing on the risk to the fetus may have medicolegal implications.

Many of the complex issues dealt with in this Report are
unlikely to be fully understood by members of the public without
professional assistance. A good source of information for a woman
or family is their obstetrical care provider who has already estab-
lished a relationship of trust. However, frequently the obstetrician
does not have the experience or knowledge to provide appropriate
counseling for all exposure circumstances and additional profes-
sional help is recommended.

Although decision making requires a consultation with a
healthcare professional, the consultation should include not only
verbal communication, but a written report with supporting infor-
mation and clarifications.