SPECIAL FOCUS

Prenatal Radiation Exposure: Background Material for Counseling Pregnant Patients Following Exposure to Radiation

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ABSTRACT

Fetal sensitivity to radiation-induced health effects is related to gestational age, and it is highly dependent on fetal dose. Typical fetal doses from diagnostic radiology are usually below any level of concern. Although rare, significant fetal radiation doses can result from interventional medical exposures (fluoroscopically guided techniques), radiation therapy, or radiological or nuclear incidents, including terrorism. The potential health effects from these large radiation doses (possibly large enough to result in acute radiation syndrome in the expectant mother) include growth retardation, malformations, impaired brain function, and neoplasia. If exposure occurs during blastogenesis (and the embryo survives), there is a low risk for congenital abnormalities. (In all stages of gestation, radiation-induced noncancer health effects have not been reported for fetal doses below about 0.05 Gy [5 rad].) The additional risk for childhood cancer from prenatal radiation exposure is about 12% per Gy (0.12%/rad) above the background incidence.

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Key Words: prenatal radiation exposure, radiation health effects, radiological emergencies, fetal radiation dose, tutorial

Pregnant women are often and understandably anxious about the health effects of environmental exposures on the fetus and particularly concerned about exposure to radiation. Unfortunately, many in the medical community are unfamiliar with the topic (as was abundantly clear following the Chernobyl nuclear power plant event in 1986, when many European women had abortions on the advice of their physicians, although the fetal radiation doses to these patients were far below any level of concern).[1] This lack of understanding may lead clinicians to provide poor advice and may leave patients confused and fearful.

Because radiation sources are ubiquitous in nature (eg, radon, cosmic radiation), all humans are exposed to a small amount of natural background radiation (approximately 0.36 rem or 0.0036 Sv/y on average).[2] (For a brief review of ionizing radiation, visit http://www.remm.nlm.gov/remm_RadPhysics.htm.) In addition to natural background radiation, radiation doses to the fetus are typically low, usually the result of diagnostic medical procedures[3] or occupational radiation exposures within the regulatory limits set by the US Nuclear Regulatory Commission (NRC) of 5 rem (0.05 Sv) per year for workers who have not declared themselves pregnant and 0.5 rem (0.005 Sv) for declared pregnant workers during the entire pregnancy.[4] (For more information on women's occupational health, visit http://www.cdc.gov/niosh/topics/women.) Nevertheless, some radiation incidents could expose an expectant mother to doses large enough to be of health concern. Interventional medical procedures (eg, "procedures comprising guided therapeutic and diagnostic interventions, by percutaneous or other access, usually performed under local anesthesia and/or sedation, with fluoroscopic imaging used to localize the lesion/treatment site, monitor the procedure, and control and document the therapy"),[5] radiation therapy,[3] or a nuclear or radiological incident (including terrorism)[6] could result in the fetus receiving high doses of radiation.

The health consequences of high radiation doses to an embryo or fetus (possibly large enough to result in acute radiation syndrome in the expectant mother) can result in intrauterine fetal demise. Even at doses too low to affect the mother immediately, radiation consequences can include growth retardation, gross congenital organ malformations (including microcephaly, hydrocephalus, porencephaly, skull malformations, hypoplastic genitalia, cleft palate, hypospadius, eye defects, skeletal defects, and neurological and motor deficiencies),[7] impaired brain function, and cancer.[3,8-16]

In an attempt to assist clinicians in treating patients who have been exposed to radiation, the Centers for Disease Control and Prevention has produced a variety of products, including fact sheets, satellite broadcasts, videos, and CD-ROM training materials (available at http://www.bt.cdc.gov/radiation/toolkit.asp). One product under development is an all-encompassing reference handbook and self-study guide to be entitled "Clinical Response to Nuclear and Radiological Incidents Including Terrorism," which will contain a chapter on prenatal radiation exposure. The present article summarizes that chapter, providing clinicians with background information regarding prenatal radiation exposure. The article is intended as an aid in counseling pregnant patients who have been exposed to radiation.

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TABLE 1

Review of Fetal Development

Stage of Gestation	Time Postconception	Substage	Description
Blastogenesis	Up to 2 wk	—	Approximately 5-7 d after conception, the blastula implants itself into the wall of the uterus, allowing connections between the mother and the embryo to form, including the umbilical cord. The embryo's growth will center around an axis, which will become the spine and spinal cord.
Organogenesis	2-7 wk	—	The brain, spinal cord, heart, and gastrointestinal tract begin to form. Brain activity will show at about the 6th wk. The heart will begin to beat and blood will start to flow at around the same time. Limb buds will appear and bones will begin to form.
Fetogenesis	8-38 wk	—	Miscarriage is much less likely in this stage than during the previous stages.
		8-15 wk	Male and female genitalia become apparent. Tooth buds appear and the limbs become long and thin. At this stage, red blood cells are produced in the liver. The majority of red blood cells are made later in gestation (at 21 wk postconception) by the bone marrow. The first measurable electrical activity in the brain occurs in the 12th wk.
		16-25 wk	The fetus has increased muscle development. Alveoli form. The respiratory system has developed to the point at which gas exchange is possible. The nervous system develops enough to control some bodily functions. The thyroid becomes hyperactive.
		26-38 wk	Body fat rapidly increases. Lungs become fully mature. Thalamic brain connections, which mediate sensory input, form. Bones are fully developed, but are still soft and pliable.

REVIEW OF FETAL DEVELOPMENT

A conceptus develops in 3 distinct stages. These are described in Table 1.

CHEMICAL TOXICITY TO THE FETUS FROM RADIONUCLIDES

In almost all cases, the toxicity of the radioactive isotopes of an element derives from the radiation emitted, not from the chemical properties of the element. For example, an ingested amount of only 100 μg of a common isotope such as cesium 137 could deliver a lethal radiation dose, but this would be far too little mass of cesium to be chemically toxic.[17] For an isotope such as polonium 210, it would require a factor of 1000 less mass to give a lethal dose from the radiation than from the chemical toxicity.[18-20] The rare exceptions to this principle are for such isotopes as uranium 238, with a half-life greater than 1 billion years.[21] Only in those cases of extremely long half-lives are the toxic chemical properties of an element of greater significance than the toxicity due to its emitted radiation. Such long-lived radionuclides have the additional challenge (depending on their chemical form) of crossing the placental barrier in quantities sufficient to be of concern to the fetus. (Only 1.8% of uranium reaching maternal blood will cross the placental barrier.)[22]

ESTIMATING THE RADIATION DOSE TO THE EMBRYO OR FETUS

Adverse health effects in the fetus depend on the fetal radiation dose and the gestational stage at the time of exposure. The fetal dose and gestational age must therefore both be estimated before potential health effects can be assessed.

Fetal dose estimations from medical exposures to pregnant women, as calculated in detail by Russell et al,[23] are found in the International Commission on Radiological Protection publication 84, Pregnancy and Medical Radiation.[3] As shown in the first 2 tables of that publication,[3] typical fetal doses from diagnostic radiology or diagnostic nuclear medicine rarely exceed 0.025 Gy (2.5 rad) for a single procedure (including a pelvic computed tomographic scan). Fetal doses below 0.05 Gy (5 rad) are considered to be low-risk exposures for which the potential risks to the fetus are likely outweighed by the benefit to the mother.

In radiotherapy (or interventional medical procedures), the dose to the fetus is dependent largely on the distance of the fetus from the radiation field. In addition, the dose to the mother from an interventional medical procedure can vary broadly, depending on the duration of the procedure.[5] Thus, there are no typical fetal doses from radiation therapy or interventional procedures to the mother. For example, fetal doses for a typical treatment regimen for brain cancer are in the magnitude of 0.03 Gy (3 rads), whereas for anterior and posterior mantle treatments of the chest for Hodgkin disease, they can be as much as 0.4 to 0.5 Gy (40-50 rad).[3] Doses for other interventional or therapeutic procedures may exceed the doses cited here and pregnant patients should discuss any risk to the fetus with their health care providers.

Resources for Fetal Dose Estimation

Therefore, for radiotherapy, as well as for nonclinical nuclear or radiological exposure incidents (including terrorism) in which fetal doses can range from no exposure to 100 Gy (10 000 rad), clinicians should consult with experts in radiation dosimetry about fetal dose estimation. Hospital medical physicists and health physicists are good resources for radiation dose estimation. In addition, in the United States, the Conference of Radiation Control Program Directors maintains a list of state radiation control/

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radiation protection contact information at http://www.crcpd.org/Map/map.html. The American Board of Health Physics maintains a listing of active certified health physicists at http://www.hps1.org/aahp/members/members.htm, and the American Board of Medical Physicists maintains a list of diplomates in medical physics specialties at http://www.abmpexam.com. Clinicians should contact these or other radiation protection organizations for assistance in estimating fetal radiation dose.

POTENTIAL NONMALIGNANT HEALTH EFFECTS OF PRENATAL RADIATION EXPOSURE

Table 2[3,8-16] summarizes potential noncancer health risks of prenatal radiation exposure. This table can assist clinicians in understanding the potential harm that can result from high exposures to radiation and in providing care to pregnant women who may have been exposed to radiation (recommendations in individual cases should be made in consultation with a hospital medical physicist or health physicist). The indicated doses and times postconception, or gestational age, are approximations.

Failure to Implant

Failure of a blastocyst to implant in the uterine wall is a common occurrence. Even in the absence of radiation exposure, implementation failure is on the order of 30% to 50%. After the embryo implants, however, the miscarriage rate decreases to about 15% for the remainder of the pregnancy. The cells then begin to differentiate into various stem cells that eventually form all the organs in the body.[8-10,12]

TABLE 2

Potential Health Effects (Other Than Cancer) of Prenatal Radiation Exposure

	Time Postconception				
				Fetogenesis	
Acute Radiation Dose* to the Embryo/Fetus	**Blastogenesis (up to 2 wk)**	**Organogenesis (2-7 wk)**	**(8-15 wk)**	**(16-25 wk)**	**(26-38 wk)**
<0.05 Gy (5 rad)† (range of most diagnostic exams)‡	Noncancer health effects *not* detectable by current diagnostic procedures				
0.05-0.50 Gy (5-50 rad)	• Incidence of failure to implant may increase slightly, but surviving embryos will probably have no significant (noncancer) health effects[3,8,12]	• Incidence of major malformations may increase slightly[8-10] • Growth retardation possible[3,13,14]	• Growth retardation following acute exposures possible[3,13,14] • Reduction in IQ possible (up to 15 points, depending on dose)[3,8-16] • Incidence of severe mental retardation up to 20%, depending on dose[3,8-16]	Noncancer health effects unlikely§	
>0.50 Gy (50 rad) (The expectant mother may be experiencing acute radiation syndrome in this range, depending on her whole-body dose)	• Incidence of failure to implant will likely be large‖ depending on dose, but surviving embryos will probably have no significant (noncancer) health effects[3,8,12]	• Incidence of miscarriage may increase, depending on dose[8-10] • Substantial risk of major malformations, such as neurological and motor deficiencies[3,13,14] • Growth retardation likely[3,13,14]	• Incidence of miscarriage probably will increase, depending on dose[8-10] • Growth retardation likely[3,13,14] • Reduction in IQ possible (>15 points, depending on dose)[3,8-16] • Incidence of severe mental retardation >20%, depending on dose[3,8-16] • Incidence of major malformations will probably increase[3,13,14]	• Incidence of miscarriage may increase, depending on dose[8-10] • Growth retardation possible, depending on dose[3,13,14] • Reduction in IQ possible, depending on dose[3,9-16] • Severe mental retardation possible, depending on dose[3,9-16] • Incidence of major malformations may increase[3,8,11]	• Incidence of miscarriage and neonatal death will probably increase, depending on dose[8-10]¶

This table is intended only as a guide. The indicated doses and times postconception are approximations.

*An acute dose is delivered in a short time (usually minutes), whereas fractionated or chronic doses are delivered over time. For fractionated or chronic doses, the health effects to the fetus would, in general, be expected to be less severe than what is depicted here for the same total dose.

†The referenced absorbed dose levels in this article are assumed to be from beta-, gamma-, or x-radiation. Neutron or proton radiation produces many of the health effects described herein at lower absorbed dose levels.

‡For example, 1 pelvic x-ray results in about 0.1 rad to the fetus, whereas 1 pelvic computed tomographic scan results in about 2.5 rad to the fetus. Occupational radiation exposures within regulatory limits also result in a fetal dose in the low dose range. Interventional medical procedures, radiation therapy, or nuclear or radiological incidents (including terrorism) could result in a fetal dose in any of these ranges.[3]

§Some researchers suggest that a small possibility exists for impaired brain function above 0.10 Gy (10 rad) in the 16- to 25-week stage of gestation.[11] However, most researchers agree that after about 16 weeks of gestation, the threshold for congenital effects in the human embryo or fetus is approximately 0.50 to 0.70 Gy (50-70 rad).[3,8-10,12-16]

‖A fetal dose of 1 Gy (100 rad) will likely kill 50% of the embryos. The dose necessary to kill 100% of human embryos or fetuses before 18 weeks' gestation is about 5 Gy (500 rad).[3,8-16]

¶For adults, the $LD_{50/60}$ (the dose necessary to kill 50% of the exposed population in 60 d) is about 3 to 5 Gy (300-500 rad) and the LD_{100} (the dose necessary to kill 100% of the exposed population) is around 10 Gy (1000 rad).

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During blastogenesis, the embryo is comprised of only a few cells. Damage to a single cell, the progenitor of many other cells, can cause the embryo's death, and the blastocyst will fail to implant in the uterus. This can occur at doses above 0.5 Gy (50 rad). Embryos that survive radiation exposure during blastogenesis likely will not have been damaged by that radiation exposure at all and, consequently, will have low risk of congenital abnormalities.[3,8,12]

Growth Retardation

Ionizing radiation can interfere with the development of the central nervous system or other major organ systems. In addition, atomic bomb survivor data show that a fetus exposed to high doses of radiation may experience permanent retardation of physical growth, and the likelihood increases with increasing dose (due to cell death), particularly above 1 Gy (100 rad). This growth retardation is most pronounced when the exposure occurs in the first 13 weeks postconception, due to the criticality of cellular activities and the high proportion of radiosensitive cells. When the dose is greater than 1 Gy (100 rad), about a 3% to 4% reduction of height is evident at age 17 years.[3,13,14]

Brain Damage

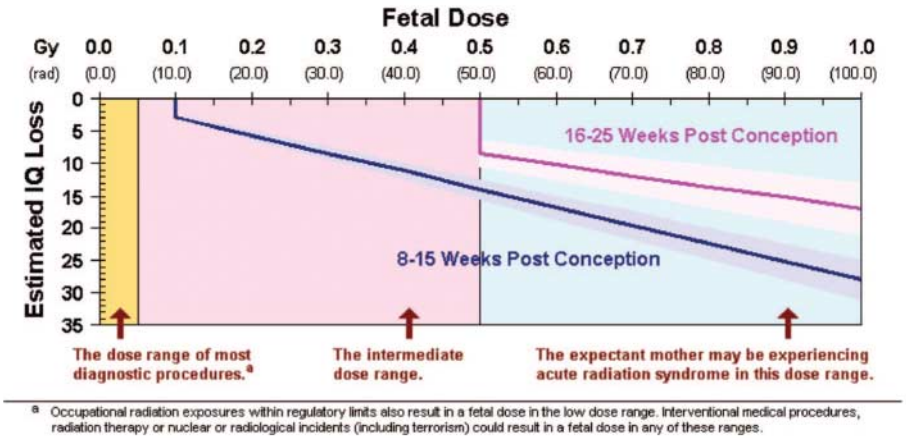
Radiation may significantly affect global brain development in a fetus exposed at 8 to 25 weeks postconception. This is due to neuron loss during the important stages of neuronal migration.

Brain Damage in the 8 to 15 Weeks Gestational Period

Atomic bomb survivor data indicate that exposures at this stage result in an average intelligence quotient (IQ) loss of approximately 25 to 31 points per Gy (100 rad) above 0.1 Gy (10 rad).

FIGURE 1

Estimated IQ loss of 2 gestational periods based on fetal dose



a Occupational radiation exposures within regulatory limits also result in a fetal dose in the low dose range. Interventional medical procedures, radiation therapy or nuclear or radiological incidents (including terrorism) could result in a fetal dose in any of these ranges.

TABLE 3

Estimated Risk for Cancer From Prenatal Radiation Exposure

Radiation Dose	Estimated Additional Childhood Cancer Incidence, %*†‡	Estimated Additional Lifetime§ Cancer Incidence, % ‖¶ (Exposure at Age 10)
0.00-0.05 Gy (0-5 rad; this is the range of most diagnostic exams)#	0.0-0.6	0-2
0.05-0.50 Gy (5-50 rad)	0.6-5.6	2-17
>0.50 Gy (50 rad; the expectant mother may have experienced acute radiation syndrome following an exposure in this range, depending on her whole-body dose)	>5.6	>17

*The background incidence of childhood cancer (onset up through age 15) is 0.3%.[3]

†Data published by the International Commission on Radiation Protection.[3]

‡Childhood cancer mortality is roughly half of childhood cancer incidence.[3]

§The lifetime cancer risks from prenatal radiation exposure are not yet known. The lifetime risk estimates given are for Japanese males exposed at age 10 y from models published by the United Nations Scientific Committee on the Effects of Atomic Radiation.[29]

‖The background lifetime cancer incidence is approximately 41%.[28]

¶Lifetime cancer mortality is roughly half of lifetime cancer incidence.[28]

#For example, 1 pelvic x-ray 0.1 rad to fetus, whereas 1 pelvic computed tomographic scan 2.5 rad to fetus. Occupational radiation exposures within regulatory limits also result in a fetal dose in the low dose range. Interventional medical procedures, radiation therapy, or nuclear or radiological incidents (including terrorism) could result in a fetal dose in any of these ranges.[3]

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Because IQ measurement sensitivity is limited in the dose range below about 0.1 Sv (10 rad), this is viewed essentially as the threshold dose below which there is little effect on IQ. When the dose is greater than 0.1 Gy (10 rad), the risk for severe mental retardation is approximately 40%/Gy (100 rad).[3,8-16]

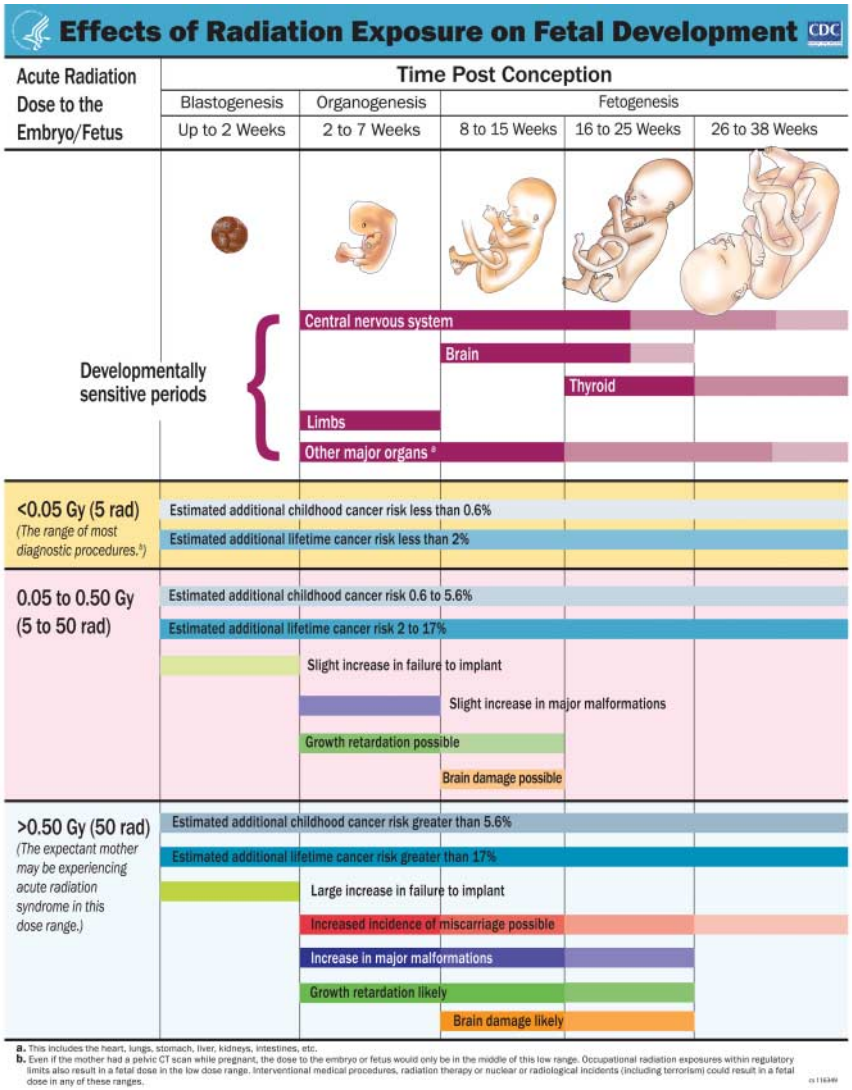
For studies of Japanese atomic bomb victims, severe mental retardation was related not to IQ but to clinical observation: "unable to perform simple calculations, to make simple conversation, to care for himself or herself, or if he or she was completely unmanageable or had been institutionalized."[13] This corresponds to an IQ<50 (0.4% prevalence in the unexposed population), although there was 1 subject whose IQ was eventually measured as high as 64.[11,13,14]

Brain Damage in the 16 to 25 Weeks Gestational Period

The central nervous system is less sensitive in the 16- to 25-week stage postconception. Still, at higher doses, the same effects seen in the 8- to 15-week stage may also occur. Although some researchers suggest that a small possibility exists for impaired brain function above 0.10 Gy (10 rad) in the 16- to 25-week stage postconception,[11] most agree that the threshold for observably impaired brain function in this period is approximately 0.50 to 0.70 Gy (50-70 rad).[3,8-10,12-15] The average IQ loss is approximately 13 to 21 points per Gy (per 100 rad) at doses

FIGURE 2

Effects of radiation exposure on fetal development



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above 0.7 Gy (70 rad), and the risk for severe mental retardation is approximately 9%/Gy (100 rad) above 0.7 Gy (70 rad)[3,9-16] in the 16- to 25-week stage. From about 16 weeks postconception to birth, radiation-induced noncancer health effects are unlikely to occur below about 0.50 Gy (50 rad).

Figure 1 depicts the degree of IQ detriment as a function of fetal dose for these 2 gestational periods.

Thyroid Damage From Radioactive Iodine

The fetal thyroid is capable of taking up radioiodines beginning approximately 70 to 80 days after conception, with uptake increasing to the time of birth.[24] If internal uptake of radioactive iodine occurs during the 16- to 25-week stage (or if an internal uptake of radioactive iodine occurs in an earlier stage and has not cleared from the mother's body by this stage), then the long-term health consequences to the offspring's thyroid (eg, spontaneous abortion, hypothyroidism, hyperthyroidism, cretinism)[7,24] should be considered. The fetal thyroid is extremely active during this period of development; if the mother ingests or inhales radioactive iodine, it will concentrate in the fetal thyroid as well as in the mother's thyroid unless the thyroid has been blocked through the use of stable iodine prophylaxis.[8,24] For information about the use of potassium iodide to protect the fetus from radioactive iodine uptake, visit http://www.bt.cdc.gov/radiation/ki.asp.

Late-Stage Miscarriage

The sensitivity of the fetus to the noncancer health effects of radiation exposure is lower during the third trimester (after about 26 weeks) than in other stages of pregnancy. Nevertheless, at doses >1 Gy (100 rad), the risks for miscarriage and neonatal death (ie, infant death within 28 days after birth, including stillbirth) increase.[3,9-16]

Most researchers agree that a dose of <0.05 Gy (5 rad) represents no measurable noncancer risk to the embryo or fetus at any stage postconception.[3,8,16,25] Research on rodents suggests a small risk for external malformations or skeletal defects as well as effects on the central nervous system in the 0.05 to 0.10 Gy (5-10 rad) range for some stages postconception.[8,11] A practical threshold for any type of congenital effects in the human embryo or fetus is, however, most likely between 0.10 to 0.20 Gy (10-20 rad).[3]

POTENTIAL CARCINOGENIC EFFECTS OF PRENATAL RADIATION EXPOSURE

Cancer risk from radiation exposure is generally considered to be proportional to dose. Latency between exposure and disease depends on many factors, but there is ample evidence that exposure in childhood reduces the time to onset.[26] Cancer at a specific time of life (eg, childhood) is generally assessed separately from a person's lifetime cancer risk. The background incidence of childhood cancer (onset up through age 15) is 0.3%.[3] The additional risk of developing a childhood cancer as a result of in utero radiation exposure is shown in Table 3; the table is based on the estimated risk of 12%/Gy (0.12%/rad) above the background incidence.[3,9,15,16] The background incidence of lifetime cancer is approximately 41% (using rates from 2001-2003, 41.28% of males and females born in the United States today will be diagnosed with cancer at some time during their lifetime).[27] Although the lifetime cancer risks from prenatal radiation exposure are not yet known because the population of atomic bomb survivors currently alive who were in utero when the exposure occurred are only 63 years old, the lifetime cancer incidence risk of 34%/Gy (0.34%/rad) above the background incidence for exposure at age 10 years also is shown in Table 3 for estimation purposes.[28]

In addition, it has not been determined whether the carcinogenic effects for a given dose vary with the timing of the exposure. At this time, carcinogenic risks are assumed to be constant throughout pregnancy.[12] Analysis of animal data suggests that, although there is a strong sensitivity to carcinogenic effects in late fetal development, exposure during blastogenesis and organogenesis is unlikely to lead to malignancy.[15]

Studies are under way to determine the lifetime cancer risk from prenatal radiation exposure. Early indications are that lifetime cancer risk from prenatal radiation exposure is similar to, or slightly lower than,[29] lifetime cancer risk from exposure in childhood. Therefore, lifetime cancer risk from childhood radiation exposure may provide a good approximation of the prenatal risk.[3,12,27,28]

CONCLUSIONS

The health consequences of high radiation doses (possibly large enough to result in acute radiation syndrome in the expectant mother) to an embryo or a fetus can be severe. Interventional medical procedures,[5] radiation therapy,[3] or a nuclear or radiological incident (including terrorism)[6] are examples of incidents that could result in high doses to the fetus. Fetal doses deriving from diagnostic studies or occupational radiation exposure, however, are usually expected to cause little or no harm.

Because fetal sensitivity to radiation-induced health effects is related to gestational age as well as to fetal dose, a visual aid may be beneficial when one is counseling pregnant patients who have been exposed to radiation. Figure 2 depicts the developmentally sensitive periods of gestation and shows the potential health effects for 3 different dose ranges.

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REFERENCES

1. Castronovo FP Jr. Teratogen update: radiation and Chernobyl. *Teratology*. 1999;60(2):100-106.
2. National Council on Radiation Protection and Measurements. *Ionizing Radiation Exposure of the Population of the United States*. NCRP Report No. 93. Bethesda, MD: NCRP; 1988.
3. International Commission on Radiological Protection. *Annals of the ICRP, Publication 84: Pregnancy and Medical Radiation*. Tarrytown, NY: Pergamon, Elsevier Science; 2000.
4. US Nuclear Regulatory Commission. Standards For Protection Against Radiation 10 CFR Part 20.1201-1208. http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/full-text.html. Accessed October 26, 2006.
5. International Commission on Radiological Protection. *Annals of the ICRP, Publication 85: Avoidance of Radiation Injury from Medical Interventional Procedures*. Tarrytown, NY: Pergamon, Elsevier Science; 2001.
6. Donnelly EH, Farfan EB, Parker DD. Potential nuclear and radiological incidents: a summary for clinicians. *Health Phys*. 2007;93(2)(Suppl): S134-S138.
7. Mettler FA, Upton AC. *Medical Effects of Ionizing Radiation*. 3rd ed. Philadelphia: Saunders Elsevier; 2008.
8. National Council on Radiation Protection and Measurements. *NCRP Report No. 128: Radionuclide Exposure of the Embryo/fetus*. Bethesda, MD: NCRP; 1998.
9. Gusev IA, Guskova AK, Mettler FA Jr. *Medical Management of Radiation Accidents*. 2nd ed. Boca Raton, FL: CRC Press; 2001.
10. National Council on Radiation Protection and Measurements. *NCRP Report No. 138: Management of Terrorist Events Involving Radioactive Material*. Bethesda, MD: NCRP; 2001.
11. Otake M, Schull WJ, Lee S. Threshold for radiation-related severe mental retardation in prenatally exposed A-bomb survivors: a re-analysis. *Int J Radiat Biol*. 1996;70(6):755-763.
12. International Commission on Radiological Protection. *Annals of the ICRP, Publication 90: Biological Effects After Prenatal Irradiation (Embryo and Fetus)*. Tarrytown, NY: Pergamon, Elsevier Science; 2003.
13. Schull WJ. *Effects of Atomic Radiation, A Half-Century of Studies from Hiroshima and Nagasaki*. New York: Wiley-Liss; 1995.
14. Hiroshima International Council for Medical Care of the Radiation-Exposed. *Effects of A-Bomb Radiation on the Human Body*. Chur, Switzerland: Harwood Academic; 1995.
15. Sasaski S, Kasuga T, Sato F, et al. Late effects of fetal mice X-irradiated at middle or late interuterine stage. *Gann*. 1978;69:451-452.
16. National Radiological Protection Board. *Documents of the NRPB 4(4): Diagnostic medical exposures: Exposure to ionizing radiation of pregnant women*. Chilton, UK: NRBP; 1993:5-14.
17. Agency for Toxic Substances and Disease Registry. *Toxicological Profile for Cesium*. Atlanta: US Department of Health and Human Services, Public Health Service; 2004.
18. Harrison J, Leggett R, Lloyd D, Phipps A, Scott B. Polonium-210 as a poison. *J Radiol Prot*. 2007;27(1):17-40.
19. Scott BR. Health risk evaluations for ingestion exposure of humans to polonium-210. *Dose Response*. 2007;5(2):94-122.
20. Brosh-Nissimov T, Havkin O, Davidovitch N, Poles L, Shapira C. Suspected radioactive contamination: evaluation of 45 Israeli citizens potentially exposed to polonium-210 in London. *Isr Med Assoc J*. 2008;10(2): 99-103.
21. Agency for Toxic Substances and Disease Registry. *Toxicological Profile for Uranium*. Atlanta: US Department of Health and Human Services, Public Health Service; 1999.
22. Sikov MR, Hui TE. *Contribution of Maternal Radionuclide Burdens to Prenatal Radiation Doses. NUREG/CR-5631 (PNL-7442), Rev 2*. Washington, DC: NRC Publications; 1996:82.
23. Russell JR, Stabin MG, Sparks RB, Watson E. Radiation absorbed dose to the embryo/fetus from radiopharmaceuticals. *Health Phys*. 1997;73(5): 756-769.
24. Agency for Toxic Substances and Disease Registry. *Toxicological Profile for Iodine*. Atlanta: US Department of Health and Human Services, Public Health Service; 2004.
25. Brent RL. Utilization of developmental basic science principles in the evaluation of reproductive risks from pre- and postconception environmental radiation exposures. *Teratology*. 1999;59:102-204.
26. National Research Council of the National Academies. *Health Risks from Exposure to Low Levels of Ionizing Radiation*. Washington, DC: National Academies Press; 2006.
27. Ries LAG, Harkins D, Krapcho M, et al. SEER Cancer Statistics Review, 1975-2003, National Cancer Institute. http://seer.cancer.gov/csr/1975_2003. Accessed October 25, 2006.
28. United Nations Scientific Committee on the Effects of Atomic Radiation. *Sources and Effects of Ionizing Radiation, United Nations Scientific Committee on the Effects of Atomic Radiation 2000 Report to the General Assembly with Scientific Annexes*. New York: United Nations Publications; 2000: 428.
29. Preston DL, Cullings H, Suyama A, et al. Solid cancer incidence in atomic bomb survivors exposed in utero or as young children. *J Natl Cancer Inst*. 2008;100(6):428-436.