Medical Imaging Radiation Safety for the Female Patient: Rationale and Implementation[1]

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For the modern practitioner of women's imaging, achieving a balance between the positive diagnostic benefits available from current medical imaging on the one hand, and the potentially deleterious effects of ionizing radiation exposure on the other, has become a central issue. Increased public and professional awareness of the side effects of radiation now require a comprehensive understanding of the facts involved, the various risks to which patients are exposed, and the measures that can be implemented to minimize these risks. The major challenges posed by pregnancy, radiosensitive breast tissue, lactation, and an inability to easily exclude ovaries from the imaging field make female patients particularly vulnerable to medical imaging radiation exposure. The nature of this vulnerability changes frequently and depends on the imaging being performed, the age of the patient, and the clinical situation. For this reason, attention to gynecologic imaging radiation exposure across the whole life span is vitally important.

Introduction

The side effects of medical imaging radiation exposure became a formidable problem for radiologists soon after Roentgen discovered x-rays and their deleterious effects first became apparent. There is little doubt, however, that the benefits of using ionizing radiation in medical imaging have considerably improved modern medical practice, and the radiology profession should be proud of the way it has continued to refine and develop this tool in a myriad of different ways to provide even more rapid and accurate diagnoses and treatment options in the gynecology arena. Computed radiography, digital radiography, fluoroscopy, computed tomography (CT), nuclear medicine, and imaging-guided therapy have progressed at an impressively rapid pace, with untold benefits to women's healthcare. However, any medical imaging that involves ionizing radiation still has inherent drawbacks and side effects, and patients, physicians, the media, and the general public all need to be aware of these potential problems.

Abbreviations: ACR = American College of Radiology, BRE = background radiation equivalent, CTDI_{vol} = volume CT dose index, DLP = dose-length product, PACS = picture archiving and communication system

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Women are particularly vulnerable to ionizing radiation. In childhood, females are more susceptible to radiation than males, largely due to superficial and dormant breast tissue. In the reproductive years, concerns are focused on preventing the inadvertent irradiation of a fetus as well as managing radiation exposure in the context of a declared pregnancy. During lactation, special procedures need to be followed in the context of some nuclear medicine examinations. It is important, therefore, that radiologists understand the background of and rationale for these concerns and are cognizant of why they have become so important in the imaging of female patients.

In this article, we discuss medical imaging radiation exposure in terms of risks and various mechanisms that can be implemented to minimize these risks, with emphasis on the female patient.

Radiation: Description and Sources

Radiation can take several different forms and is simply a mechanism whereby energy is transmitted through space. Medical imaging modalities that involve ionizing radiation make use of electromagnetic waves located near one end of the electromagnetic spectrum. This spectrum consists of differing electromagnetic waves that are defined by their electromagnetic wavelength. At one end of the spectrum are the long-wavelength and relatively innocuous radio- and microwaves. As the electromagnetic wavelength decreases, radiation passes through the spectrum of visible light, after which the short-wavelength, high-energy x-rays, gamma rays, and cosmic rays are encountered. This energy has the capacity to be harmful to biologic tissue because it carries the potential to displace electrons from its energy level or shell around the nucleus. This can lead to ionization of the affected atom and explains why these forms of electromagnetic waves are termed "ionizing radiation." The effects of ionizing radiation on biologic tissues at the atomic and molecular level are concerning for several reasons. First, a displaced electron can cause damage to other cell components as it is ejected rapidly from its orbit. Second, the resulting highly chemically reactive ionized atom, or "free radical," can have deleterious effects on the cell of which it is a part. Third, the altered structure of the atom that occurs once an electron is lost may affect the function of the tissue involved (1); this result may be particularly grievous if the involved tissue is a chromosome within a radiosensitive cell such as those found in the breast or ovary. Because ionizing radiation can cause these associated effects within a patient, it is best to make sure that any ionizing radiation exposure from imaging is appropriately justified and that the benefits far outweigh the associated risks. It is also important to understand the origins of ionizing radiation and the various sources of human exposure.

Humans are exposed to unavoidable forms of ionizing radiation each day. This type of radiation is classified as background radiation and is an unavoidable consequence of living. Background radiation originates from radon gas seeping out of the earth, natural radioactivity being emitted from rocks and other organic compounds in the ground, and cosmic rays that constantly rain down from space, among other sources. The level of background radiation varies considerably across the globe; a "standard person" in the United States is exposed to an average of approximately 3.1 mSv per year (2), whereas persons in Kerala, India can be exposed to up to 70 mSv per year due to the naturally occurring thorium-coated monazite sand that is found there (3). As recently as 2005, background radiation was understood to be the major source of radiation exposure to the U.S. population, with man-made radiation sources (which include medical imaging) accounting for only a small proportion of overall radiation exposure. However, recent data have shown that man-made radiation sources now contribute almost the same amount of exposure to the U.S. population each year as background radiation (Fig 1) (4). Although man-made radiation sources include airport security scanners, smoke detectors, television sets, and fluorescent lamp starters, medical imaging accounts for 95% of all exposure from man-made radiation sources (5). The reason for this rapid alteration in the proportions of exposure from man-made radiation sources over the past few years has been the phenomenal increase in the use of ionizing radiation in medical imaging: In the United States, medical imaging radiation exposure rose from 0.54 mSv per person in 1980 to 3.0 mSv per person in 2006 (2), nearly a sixfold rise.

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Medical Imaging Radiation Risks

Given that the majority of radiation exposure is now from man-made sources and that the majority of this exposure originates from medical imaging, it is important to understand the possible effects and risks of this radiation exposure for the human body. Radiation effects can be divided into two general types: deterministic effects and stochastic effects (Table 1).

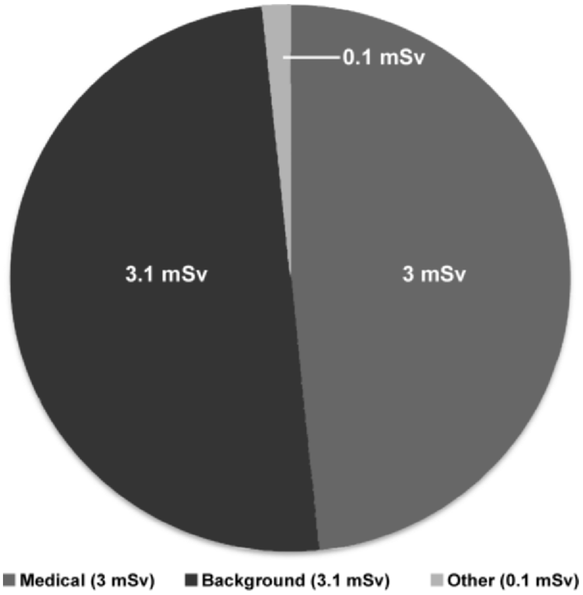

Figure 1. Chart shows the sources of radiation exposure in the United States in 2006.

Table 1
Types of Radiation Effects

Type	Effects
Deterministic	Erythema, epilation, skin necrosis, cataract formation
Stochastic	Carcinogenesis, hereditary effects

Deterministic effects are the result of the excessive cell death that can occur following ionizing radiation exposures. These effects include skin erythema, epilation, necrosis, and lens cataract formation. Because these effects occur only after a critical mass of cells have died, they have a known radiation exposure threshold below which their occurrence can be avoided. Once these adverse effects were determined, it paved the way for a radiation protection agenda with the creation of the International Commission of Radiological Protection in 1928 (6). Inadvertent deterministic effects have recently been reported in women following interventional procedures (7,8) and even following CT (9), with radiation burns, hair loss, and skin necrosis being graphically illustrated. These examples serve as a good reminder of the potentially detrimental radiation doses that some of today's medical imaging devices can relatively easily impart.

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Stochastic radiation effects are understood to have no threshold level below which they do not occur. Unlike with deterministic effects, the severity of stochastic effects does not increase with dose, but the likelihood of an effect taking place does increase. Stochastic effects include carcinogenesis and hereditary effects. The possibility of a stochastic effect taking place supports the practice of exposures being kept as low as reasonably achievable (ALARA).

Anecdotal evidence from the past showed that patients undergoing radiation treatment for benign conditions such as thymic hypertrophy, tinea capitis, or adenoidal enlargement had a propensity to develop tumors in the exposed areas. Later studies showed that girls exposed to x-rays from multiple screening chest radiographs for tuberculosis or radiographs for scoliosis were more prone to develop breast cancer than were girls who had undergone no imaging (10). In patients who underwent radiography for scoliosis, after a follow-up of 47 years, mortality from breast cancer was 8% higher in the imaged cohort (11). These studies add credence to the current understanding of cumulative radiation exposures, according to which excess cancer risk is increased in females and in children of either gender who are exposed at a young age (12). However, even more convincing evidence that medical imaging radiation exposure can cause cancer is based on data generated by the Radiation Effects Research Foundation. This collaboration between the American and Japanese governments has studied a large cohort ($n = 90{,}000$) of survivors of the Hiroshima and Nagasaki atomic bomb drops since 1950. These individuals were exposed to varying degrees of radiation and have been studied for the development of cancer over the past 65 years. Data on cancer occurrence in these individuals have been compared with data in controls, and the results to date show that there is a small but direct, statistically significant increased relative risk for cancer mortality following relatively low-dose exposures (5–125 mSv) (13). On the basis of data from this and other studies, it has been proposed that the excess relative risk of cancer mortality from imaging studies exposing women to 10 mSv of radiation is approximately one in 2000 (14). This risk varies depending on certain parameters, but women have been shown to be more sensitive than men (12) and girls twice as sensitive to radiation-induced cancers as boys (15). However, it is also important to consider other aspects of risk in a patient's medical course. Although the risk from ionizing radiation exposure should always be considered, it must be weighed against the risks inherent in not promptly diagnosing or correctly treating the patient's condition. For example, the risks to the patient and fetus from a potential

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maternal pulmonary embolus far outweigh those from radiation imparted by CT pulmonary angiography (16).

Medical Imaging Doses

It is important to understand the various units used to measure radiation exposure. These units relate to different ways of describing ionizing radiation exposure and include absorbed dose (measured in grays [Gy] or rad) and effective dose (measured in sieverts [Sv] or rem). Absorbed dose is simply a measurement of the total amount of radiation energy absorbed per volume of tissue exposed. As such, absorbed dose provides little information on biologic effects, and although it can be used to compare the different amounts of radiation to which the whole body has been exposed from different imaging sources, it bears no relation to the type of tissues involved. Effective dose is a much more relevant measurement, given that a weighting factor is applied to the radiation dose; this factor is determined on the basis of the tissue or organs exposed as well as the type of radiation involved. The weighting factor represents the proclivity of a tissue to develop stochastic effects, with (for example) breast (0.12) and ovaries (0.08) having a greater weighting factor than brain or salivary glands (both 0.01) (17). Thus, identical ionizing radiation exposures to the breast and head might have similar absorbed doses, but the breast exposure would have a much higher effective dose, reflecting the increased cancer risk.

The radiologist should have a clear understanding of the relative dose weightings of various imaging procedures. It is important to keep in mind that effective dose is an estimate of the radiation effect to a population, not to a specific patient or group. These estimates are based on an idealized standard man and woman. With that said, converting the dose used for a study into a "background radiation equivalent" (BRE) is helpful in counseling patients and educating referring clinicians (Table 2). The average background effective dose in the United States is approximately 3.1 mSv per year. A single frontal chest radiograph has an approximate effective dose of 0.02 mSv and therefore a BRE of 2.3 days. A pelvic radiograph has a higher effective dose (~0.6 mSv, BRE = 71 days) due to the involvement of the ovaries and the density of the involved tissue. Modern screening mammography has an effective dose of about 0.4 mSv (BRE = 47 days), but a barium enema study has a much higher effective dose of 8 mSv (BRE = 2.6 years). However, the highest gynecologic study doses originate from CT scans and fluoroscopic interventional procedures. CT of the chest, abdomen, and pelvis can result in an effective dose of approximately 21 mSv (BRE = 6.7 years), and an interventional study such as uterine-pelvic vein embolization can have an effective dose of roughly 60 mSv (BRE = 19.3 years) (18).

Table 2
BREs for Various Gynecologic Imaging Studies

Study	Dose (mSv)	BRE
Frontal chest radiography	0.02	2.3 d
Mammography	0.4	47 d
Pelvic radiography	0.6	71 d
Bone scintigraphy	6.3	2 y
Barium enema study	8	2.6 y
FDG PET scintigraphy	14.1	4.5 y
Chest/abdominopelvic CT	21	6.7 y
Uterine-pelvic vein embolization	60	19.3 y

Note.—FDG = 2-[fluorine-18]fluoro-2-deoxy-D-glucose, PET = positron emission tomography.

Although interventional radiologic procedures can impart a considerable radiation exposure, CT is a greater source of radiation to the female population as a whole. The number of CT studies performed has increased considerably over the past 20 years, in part because of its accessibility, the increased number of clinical indications, and its speed of acquisition. In 2006, CT accounted for nearly one-half of all radiation exposure to the U.S. population from medical imaging, despite accounting for only 17% of all imaging procedures (Table 3) (2).

Age, pregnancy, and lactation status also play important roles in determining a patient's radiation risk from gynecologic imaging. The excess relative risk of carcinogenesis from radiation is nearly three times higher in children under the age of 10 years than in the population as a whole (19). This can be explained by *(a)* the growing child's high rate of mitosis; *(b)* his or her longer life expectancy, during which a radiation-induced malignancy may develop; and *(c)* the difficulty in limiting exposures to nonradiosensitive areas due to his or her small size. The gravid uterus is

Table 3
Medical Radiation Exposure to the U.S. Population in 2006

Procedure	No. of Procedures ($\times 10^6$)*	Collective Dose (person-Sv)*	Dose Per Capita (mSv)
Radiography	281 (73)	96,000 (11)	0.3
Interventional procedures	17 (4)	129,000 (14)	0.4
CT	67 (17)	440,000 (49)	1.5
Nuclear medicine	19 (5)	231,000 (26)	0.8
Total	384 (100)	~900,000 (100)	~3.0

Source.—Reference 2.
*Numbers in parentheses indicate (rounded) percentages.

also a radiosensitive organ owing to the developing fetus, and theoretic effects from radiation (based on animal and human studies) include prenatal death, growth retardation, mental retardation, and childhood cancer (20). However, doses under 50 mGy (10 mSv) have not been associated with an increase in fetal anomalies or pregnancy loss (21), which is reassuring given that an estimated dose to the conceptus (ie, embryo or fetus) from abdominopelvic CT is approximately one-half this amount (20). Although animal studies have demonstrated no increased radiation risk to the lactating breast vis-à-vis the nonlactating breast (22), lactation status has important implications for nuclear medicine, in which inadvertent exposure of the nursing child to radioisotopes should be avoided. Maternal radiopharmaceuticals can be excreted in breast milk and, if ingested by the child, may accumulate within the child's organs. For example, it has been calculated that imaging with sodium iodide iodine-131 can deliver an effective dose of 5400 mSv/MBq to the neonatal thyroid gland (23). As a result, temporary or permanent cessation of breast-feeding following the administration of certain radiopharmaceuticals is suggested (23).

The breast is an organ that deserves particular mention in the context of radiation exposure because of its radiosensitivity, high incidence of inherent malignancy, and superficial location on the chest wall. The breast is frequently exposed to ionizing radiation during chest imaging, one of the most commonly performed imaging studies. For example, in the workup of a patient with a suspected pulmonary embolus, the dose to the breast from CT pulmonary angiography is higher than that from a ventilation-perfusion scan (16). However, CT pulmonary angiography is the most commonly used imaging tool for detecting pulmonary emboli—and patients are often young, female, or both. In one study, 60% of CT pulmonary angiographic examinations were performed in women, 25% of whom were under 40 years of age (24).

Dose Reduction Implementation

Dose reduction initiatives in gynecologic imaging can be divided into *(a)* examination-specific strategies and *(b)* general strategies.

Examination-specific Strategies

Computed-Digital Radiography.—Relatively simple techniques and protocols in computed-digital radiography practice can reduce the dose burden to female patients. For example, having the patient empty the bladder before undergoing radiography of the lumbar spine can reduce the dose to the ovaries by over 40%, since the ovaries are more likely to have moved outside the field of view (25). The concept of appropriate and effective gonadal shielding is also important to consider when imaging a young female patient; it fosters reassurance and comfort to the parent or caregiver and reduces radiation exposure to the patient. However, studies have shown that these shields are often inaccurately placed and provide little or no protection to the ovaries. In one study of radiographs obtained in several thousand girls, gonadal shields were accurately placed in just over one-quarter of cases (26). Responsible radiology departments can easily review the correct location of the ovaries and the best way to protect them with appropriate shielding (Fig 2) (27), as well as supervise maneuvers such as bladder emptying.

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Fluoroscopy.—Dose exposure reduction in fluoroscopic procedures requires attention to detail and a vigilant approach to protocols. Although some aspects of traditional hysterosalpingography have been replaced by sonohysterography and pelvic magnetic resonance imaging, conventional fluoroscopic hysterosalpingography may still be required. A conventional hysterosalpingographic examination has the most stringent dose reduction requirements, since patients are usually young and attempting pregnancy; yet, by definition, evaluation of the involved area requires exposure to the uterus and ovaries. Pregnancy testing prior to the examination is a mandatory component of the study protocol, although studies performed inadvertently on pregnant patients have been described (28). Studies have also shown that the radiation dose from hysterosalpingography has fallen as the number of required exposures and views has been reduced. Although dose reduction can also be achieved with modern technologic advances in the form of pulsed and digital fluoroscopy, factors such as limiting magnification and reducing the image receptor–to-skin distance can also be used (29). Other basic approaches to fluoroscopy that can easily be implemented to reduce radiation exposure include setting an audible alarm to go off after the passage of a certain amount of study time, removing the grid for the imaging of small patients, reducing ambient lighting to maximize screen visibility, and avoiding radiosensitive areas whenever possible. Educational materials such as the "Step Lightly" campaign from the Society for Pediatric Radiology (30) are an ideal resource for identifying and reinforcing these techniques.

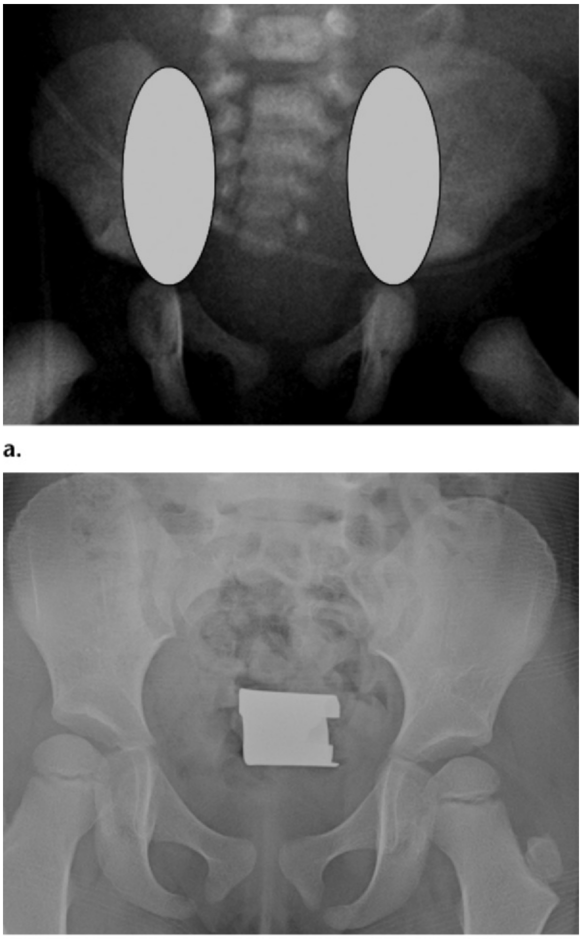

Figure 2. Anteroposterior pelvic radiographs show correct **(a)** and incorrect **(b)** positioning for female gonadal shields. Note that correct positioning obscures a significant amount of the pelvis and would not be appropriate in many clinical situations (eg, trauma).

Computed Tomography.—The main practical steps to reducing radiation exposure from CT include modifying the parameters for milliampere-seconds and kilovolt peak in imaging protocols and, in certain situations, considering the use of bismuth latex breast shields.

The CT tube current, or milliamperage, is directly proportional to the dose received by the patient, and keeping this operator-dependent parameter as low as possible is vital for successful dose reduction. However, a milliamperage that is too low will result in increased noise; thus, a balance needs to be struck between use of the lowest possible dose and preservation of image quality. Most modern scanners make use of automatic exposure control or tube current modulation (31), features that automatically reduce the tube current as the radiation beam passes through less dense or less thick tissue. Attenuation is calculated from the scout image, and the milliamperage is adjusted accordingly depending on the body part being examined or the type of study. Given that the scout image determines the attenuation, it is vital that the patient is centered in the gantry appropriately, since differences in table height can alter the attenuation calculations (32). The image should be optimized for the study type, rather than simply for the body part being imaged. For example, diagnostic abdominal CT performed in a patient with an ovarian carcinoma would require a higher milliamperage than would abdominal CT for renal calculi.

Attention to the peak tube potential, or kilovolt peak, can also be helpful in image dose reduction. Although a low kilovolt peak results in a reduced dose and increased noise, it also has the benefit of increased contrast resolution (33). This occurs in part because the mean photon energy

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at 80 kVp is closer to the k edge of iodine (32 keV) than at higher kilovolt peak settings. This may be of particular importance in contrast material–enhanced studies (in which the conspicuity of enhancing structures is maximized) and in studies aimed at stone detection.

The increased noise encountered at low–kilovolt peak scanning is also less manifest in small patients (such as young girls); thus, kilovolt peak settings need to balance the increased noise and contrast resolution against patient size and the purpose for the study. Taking these factors into account means that high-quality, dose-responsible CT protocols can be created.

Bismuth latex shields can be placed over tissues that are superficial but radiosensitive, such as the thyroid gland, lens, or breast tissue (developed or dormant). These shields generate minimal image distortion and can result in dose reductions to the anterior surface of the breast of up to 40% (34). Although the use of shields provides reassurance and a feeling of protection to the patient, a concerted effort at reducing tube current has been shown to provide similar dose reduction results with no image distortion (35).

General Strategies

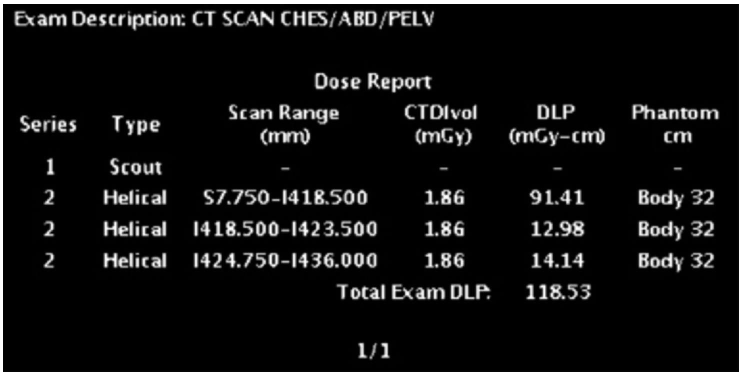
Ionizing radiation has been classified as a carcinogen by the World Health Organization (36) and many other health-related agencies, and is therefore in the same category as asbestos and benzene, substances in which considerable effort and costs are expended in dealing with compensation, litigation, and exposure prevention. It is unlikely that ionizing radiation (and medical imaging ionizing radiation in particular) will escape this type of scrutiny in the foreseeable future given its carcinogenic status. Indeed, the Joint Commission recently issued a sentinel alert on this topic (37). We may expect additional legislation governing ionizing radiation exposure from medical imaging to be enacted in the near future because, apart from mammography, there is to date no federal legislation in the United States regulating the use of medical imaging ionization radiation exposure devices (38).

Justification

Europe has a much lower medical imaging radiation exposure level per capita than the United States (2). This may be due in part to the European Commission Directive (39), which has empowered member countries to enact legislation such as the United Kingdom's Ionising Radiation (Medical Exposure) Regulations (40). These regulations legally empower radiologists to justify each exposure before it takes place and consequently provide fertile ground for referrer education and appropriateness awareness. However, educating referrers by means of radiologist justification can be time consuming and sometimes combative. An alternative mechanism that is likely to improve request justification with a minimum of clinical disruption is the concept of decision support. The American College of Radiology (ACR) has created image appropriateness criteria (41) that determine the appropriateness (and relative radiation value) of an investigation on the basis of the indications and clinical details provided by the requestor. In this way, the most clinically relevant and radiation-appropriate study can be identified. This has been shown to be particularly effective in reducing exposure to ionizing radiation from medical imaging when linked electronically to a computerized physician order entry system (42). For example, when a clinician orders CT for suspected ovarian torsion, the program would suggest to the clinician that ultrasonography is the more appropriate examination, and the clinician can order that examination instead. The physician has the ability to override this suggestion; to date, however, users have demonstrated an increase in diagnostic yield and reduction in exposure with such programs (43).

Dose Registry

Knowing the approximate dose a CT scan imparts to an individual patient is fundamental to a departmental program for responsible dose reduction. Modern CT scanners generate a dose report, which usually contains information on the study's volume CT dose index ($\mathrm{CTDI}_{\mathrm{vol}}$) and dose-length product (DLP). $\mathrm{CTDI}_{\mathrm{vol}}$ is a measurement of radiation output imparted by the scanner to an acrylic "typical adult" or "typical pediatric" phantom using the parameters set by the technologist for that examination (44). Therefore, the resulting $\mathrm{CTDI}_{\mathrm{vol}}$ bears no relation to the body part being imaged or the sex, age, or size of the patient. DLP is simply the product of $\mathrm{CTDI}_{\mathrm{vol}}$ and scan length (in centimeters). Most institutions now upload these dose reports to a picture archiving and communication system (PACS) (Fig 3) so that radiologists and referrers are able to reference the appropriate radiation metrics. Although DLP is not a representation of dose received by the individual patient per se, a conversion factor for various body parts can be applied to obtain an approximate effective dose (45). This is the mechanism used for ACR CT accreditation criteria and is particularly useful in pediatric imaging (in which differences in dose



Exam Description: CT SCAN CHES/ABD/PELV

Dose Report

Series	Type	Scan Range (mm)	CTDIvol (mGy)	DLP (mGy–cm)	Phantom cm
1	Scout	–	–	–	–
2	Helical	S7.750-1418.500	1.86	91.41	Body 32
2	Helical	1418.500-1423.500	1.86	12.98	Body 32
2	Helical	1424.750-1436.000	1.86	14.14	Body 32
			Total Exam DLP:	118.53	

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Figure 3. Screen shot shows a typical PACS CT dose report.

between adult and pediatric CT technical protocols can be demonstrated) and in patients of any age in whom anomalous imparted doses are identified. A dose report on a PACS makes these cases readily apparent and facilitates investigation and root cause analyses to prevent future occurrences. Applying this form of dose monitoring on a wider scale is currently being undertaken by the ACR Dose Index Registry program (46). With this program, institutions can subscribe to a service whereby each CT scan dose report is automatically sent to a central repository where local figures are compared with national benchmarks for the test in question. In this way, outlying institutions can easily be identified, their protocols subsequently optimized, and their doses consequently reduced.

Conclusions

Implementing reductions in radiation exposure and an awareness of the consequences of such exposure at gynecologic imaging can be undertaken at both the local and wider level. This article has explained the rationale for limiting medical imaging radiation exposure in female patients and has identified several implementation strategies for dose reduction. Addressing these issues will help encourage the use of safe, appropriate, and high-quality protocols in women's imaging.

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Medical Imaging Radiation Safety for the Female Patient: Rationale and Implementation

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Page 1830
In the United States, medical imaging radiation exposure rose from 0.54 mSv per person in 1980 to 3.0 mSv per person in 2006 (2), nearly a sixfold rise.

Page 1831
Inadvertent deterministic effects have recently been reported in women following interventional procedures (7,8) and even following CT (9), with radiation burns, hair loss, and skin necrosis being graphically illustrated.

Page 1831
Data on cancer occurrence in these individuals have been compared with data in controls, and the results to date show that there is a small but direct, statistically significant increased relative risk for cancer mortality following relatively low-dose exposures (5–125 mSv) (13).

Page 1833
For example, having the patient empty the bladder before undergoing radiography of the lumbar spine can reduce the dose to the ovaries by over 40%, since the ovaries are more likely to have moved outside the field of view (25).

Page 1834
Although a low kilovolt peak results in a reduced dose and increased noise, it also has the benefit of increased contrast resolution (33).