Imaging Strategies to Reduce the Risk of Radiation in CT Studies, Including Selective Substitution With MRI

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“...When one admits that nothing is certain one must, I think, also admit that some things are much more nearly certain than others.” Bertrand Russell (1872–1970)

Computed tomography (CT) is one of the largest contributors to man-made radiation doses in medical populations. CT currently accounts for over 60 million examinations in the United States, and its use continues to grow rapidly. The principal concern regarding radiation exposure is that the subject may develop malignancies. For this systematic review we searched journal publications in MEDLINE (1966–2006) using the terms “CT,” “ionizing radiation,” “cancer risks,” “MRI,” and “patient safety.” We also searched major reports issued from governmental U.S. and world health-related agencies. Many studies have shown that organ doses associated with routine diagnostic CT scans are similar to the low-dose range of radiation received by atomic-bomb survivors. The FDA estimates that a CT examination with an effective dose of 10 mSv may be associated with an increased chance of developing fatal cancer for approximately one patient in 2000, whereas the BEIR VII lifetime risk model predicts that with the same low-dose radiation, approximately one individual in 1000 will develop cancer. There are uncertainties in the current radiation risk estimates, especially at the lower dose levels encountered in CT. To address what should be done to ensure patient safety, in this review we discuss the “as low as reasonably achievable” (ALARA) principle, and the use of MRI as an alternative to CT.

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Key Words: computed tomography; ionizing radiation; cancer risks; MRI; patient safety

AN IMPORTANT TRANSLATION from laboratory investigation to clinical practice occurred with the discovery of x-rays by Wilhelm Roentgen in 1895, which gave birth to the profession of diagnostic radiology. In the 1970s Godfrey Hounsfield developed the first commercial computed tomography (CT) scanner, which used computer technology to help transform the practice of radiology. The diagnostic value of CT when it is used judiciously for specific indications is unquestioned. For example, CT is unmatched in its ability to demonstrate findings in major trauma, renal stone disease, and interstitial lung disease (1,2). Recent advances in high-speed multidetector row CT technology have enabled radiologists to obtain clearer images in shorter times, and have markedly increased the use of CT (3).

However, with increased use comes growing concern regarding the possible risks associated with ionizing radiation from diagnostic CT. In this article we review publications regarding the hazards of x-rays, and discuss the lack of awareness by both medical practitioners and the general population concerning the potential harmful effects of x-rays. We also address current uncertainties regarding the radiation risks of CT doses, and propose ways in which the medical community can modify its behavior in the light of the controversies associated with the radiation risk of low doses. We outline how one can reduce individual and collective patient doses from CT without detracting from the valuable diagnostic information that this important imaging modality affords health-care providers. One component of this strategy is to substitute CT with MRI studies when clinically appropriate.

RADIATION RISKS

Patients undergoing a CT examination typically receive organ doses on the order of tens of mGy. As a result, organ doses in CT are well below the threshold doses for the induction of deterministic effects such as skin burns and epilation, and the induction of eye cataracts (4). In the middle of the 20th century, when atmospheric testing of atomic weapons resulted in radioactive fallout on a worldwide scale, the genetic effects of radiation were deemed to be a major concern. Nowa-
days, however, any genetic risk is considered to be minor compared to the risk of carcinogenesis. Individual genetic risks are regarded as negligible, and any corresponding societal impact from diagnostic radiology is deemed to be very low. The principal concern at patient doses on the order of tens of mGy is the induction of fatal and nonfatal cancers (5–7).

Radiation delivered by x-ray-based imaging modalities has been shown to result in deleterious health effects. Publications in the 1940s and 1950s described the increased incidence of leukemia in radiologists (8,9). Fluoroscopy was a major form of imaging investigation at that time, which explains why radiologists had a higher incidence of leukemia (since with this method the radiologist and patient share the same radiation exposure). One of the earliest reports that described the development of leukemia in children as a result of x-ray exposure of the maternal abdomen during pregnancy was published in 1956 (10). This study involved a nationwide survey across England, and the preliminary findings were that 85 patients with leukemia had been exposed to radiation from maternal abdominal x-rays, while 45 patients had not. The authors concluded that “so large a total difference between the cases and controls can hardly be fortuitous” (10). They also explained that “one reason for attempting a nation-wide survey was the possibility that the peak of leukemia mortality noted by Hewitt (11) might be explained if weak irradiation could initiate changes in a fetus or very young child.” Their concluding statement was that “this apparently harmless examination may occasionally cause leukemia or cancer in the unborn child.” A follow-up review published in 1987 (12) considered that a causal explanation is supported by evidence indicating an appropriate dose-response relationship, as well as by animal experiments, and concluded that radiation doses on the order of 10 mGy received by the fetus in utero produce a consequent increase in the risk of childhood cancer (12). They reported that the excess absolute risk coefficient is approximately 6% per gray of radiation exposure (12). Historical data from the early days of diagnostic x-ray imaging indicate that malignancies arose from excessive exposure to the x-rays. A number of articles in major medical journals described various malignancies those arose in both patients and physicians (8,9). Other data showed an increased risk of breast cancer in female patients who underwent serial spine x-ray examinations for investigation of scoliosis (13), and an increased incidence of childhood leukemia associated with postnatal diagnostic x-rays (14). These studies involved relatively high organ doses. Unfortunately the doses were not recorded, but they may be much higher than the organ doses associated with individual CT examinations.

Organ doses associated with routine diagnostic and elective CT scans are similar to the low-dose range of radiation received by atomic-bomb survivors, who have manifested significant increases in cancer incidence and mortality (15–17). The individuals in the lowest dose group of atomic-bomb survivors who showed a significant rise in cancer incidence and mortality received organ equivalent doses1 in the range of 5–100 mSv (mean equivalent dose = 29 mSv) and 5–125 mSv (mean equivalent dose = 34 mSv), respectively (15,16). Typical equivalent doses in directly irradiated organs are in the range of 20–30 mSv for a single routine adult CT examination (18,19). Although the form of radiation delivered by atomic bombs (gamma radiation) is different from that used in radiology (x-radiation), there is fundamentally no difference in the carcinogenic potential (4). The average number of CT scans conducted for a given medical problem is two, yielding an average total equivalent dose of 40–60 mSv (17,19,20). Of particular concern are CT studies involving the liver, pulmonary embolism, and renal calculi. This reflects the high dose per procedure (liver), the territory of coverage (pulmonary embolism), and the likelihood of repeat studies (renal calculi). CT pulmonary angiography delivers a high radiation dose to the breasts of young women, and thus has a tremendous potential to induce breast cancer (21). An important area of potential CT overuse is the investigation of renal calculi. One recent study assessed repetitive studies in patients with suspected renal stones, and found that over a six-year period 4% of patients underwent three or more CT studies for this indication, with estimated effective doses ranging from 19.5 to 153.7 mSv (22). One factor hindering the widespread recognition of the harmful effects of CT is the absence of direct data regarding cancer induction from CT. One study reported on induction of DNA double-strand breaks with CT in lymphocytes of subjects undergoing CT examination (23). DNA double-strand breaks may be viewed as a step in the pathway to carcinogenesis. Thus, there are data indicating an increased cancer risk at doses used in diagnostic CT, and the potential for adverse consequences that may arise from increasing CT utilization needs to be addressed.

One can assess the radiation risk to any single tissue by considering the organ dose. A CT scan will normally irradiate many organs and tissues, and it is the total patient risk that is of interest. The effective dose takes into account all of the irradiated organs and tissues, as well as their radiosensitivities, and is the best single parameter for quantifying how much radiation an individual will receive during any radiologic examination (24). The effective dose, expressed in mSv, is the product of an organ’s equivalent dose and radiosensitivity, and is obtained by summing over all exposed organs and tissues (5). An effective dose provides the whole-body dose that produces the same risk as a partial dose delivered by a localized radiologic procedure (25), and a uniform whole-body dose of 1 mGy corresponds to an effective dose of 1 mSv. Effective doses may also be converted into a numerical risk of mortality from radiation-induced cancer (26), which is currently taken to be on the order of 5%/Sv when averaged over a whole population (5). The pediatric population represents an especially vulnerable group of individuals who are at increased risk for cancer (27). This fact is underscored

1The equivalent dose (mSv) is the absorbed dose (mGy) multiplied by the radiation weighting factor wr, which depends on the type of radiation. X-rays, gamma rays, and beta particles have wr equal to 1, while alpha particles and neutrons have wr values of 20.
by a recent article in the *Journal of the American Medical Association* regarding a long-term follow-up (55–58 years) of atomic-bomb survivors exposed to radiation (28). The authors concluded that a significant linear dose-response relationship existed in the prevalence of malignant thyroid tumors, and that the relationship was significantly higher in individuals exposed at younger ages (<20 years). At the same technique factors, as used in adults, pediatric doses are substantially higher (29), and young children have a higher radiosensitivity than adults (19,30,31). For example, recent studies have shown that 600,000 abdominal and head CT examinations annually in children under the age of 15 years could result in 500 deaths from cancer attributable to CT radiation (32). The most common malignancies associated with radiation exposure include leukemia and breast, thyroid, lung, and stomach cancers (33). It is important to note that the latency period for solid cancers is generally long (10–20 years on average) and persists throughout life (34). Of all malignancies, leukemia has the earliest latency period, with increased risks being noted at two to five years following radiation exposure (34).

**HOW WELL ARE CT DOSES (AND RISKS) UNDERSTOOD?**

It is important to realize that CT doses are much higher than conventional radiography doses (7,35–38), and that the effective dose for a chest CT is approximately 100–1000 times larger than that for a corresponding chest x-ray examination. Table 1 shows the average effective doses used in 16 common x-ray procedures in 19 western countries, and illustrates that patient doses in CT are much higher than those in most common radiographic examinations (7). Furthermore, published frequency data mask the number of times a single patient receives multiple CT examinations (37) and the common practice of multiphase CT scanning, both of which increase the radiation dose (and potential risk) in a cumulative manner (20,39). It has been estimated that 30% of all individuals who undergo CT will be examined at least three times (37).

It is important to realize that the imaging-based radiation risk for the individual patient is small compared to the overall risk for developing cancer from all causes (approximately 42 per 100 individuals) (33). However, from a public health risk perspective, this small individual cancer risk must be multiplied by a large and ever-increasing population of individuals undergoing CT examinations. A small excess mortality risk of 0.05% for cancer attributable to ionizing radiation exposure for an individual translates into 50 radiation-induced deaths per 100,000 people exposed (40). Such a risk could be extrapolated from an effective dose of 10 mSv, which is incurred from a single CT examination (40).

The FDA estimates that a CT examination with an effective dose of 10 mSv (e.g., one CT of the abdomen) may be associated with an increased chance of developing fatal cancer for approximately one patient in 2000 (41). An estimate of the lifetime cancer mortality risk attributable to the radiation exposure from a single abdominal CT examination in a one-year-old child is approximately one in 550 (32). A recent report by de Gonzalez and Darby (42) estimated that, per year, diagnostic x-ray use in the United States causes 0.9% of the cumulative risk of cancer to age 75 in men and women, which is equivalent to 5695 cases. These statistics indicate the potential for a future public health problem, given that over 60 million CT scans are currently performed annually in the United States (20,43) and the use of this modality is continuing to grow rapidly (44).

Despite the current evidence regarding the risk of low-dose radiation offered by radiation biologists, there is a lack of information transfer between researchers and clinicians, including radiologists. In a recent study of health policies and practices in radiology, Lee et al (3) considered adult patients who were seen in the emergency department of a U.S. academic medical center for mild to moderate abdominopelvic or flank pain and underwent a CT investigation. Only 7% of the patients stated that they were informed about the risks and benefits of a CT scan. More importantly, only 3% of the patients reported that they were informed about the increase lifetime cancer risk associated with CT. Referring emergency department physicians were also largely unaware that there were any potential harmful effects from the radiation exposure (only 9% were aware of the increased cancer risk). Of even greater concern are data showing that the radiologists who performed the CT examinations considered the radiation exposure to be of limited importance, and were unaware of the amount of radiation that was delivered to the patients by CT. Another recent study from a large hospital in the UK used a simple questionnaire with a multiple-choice format to assess the knowledge of primary care and specialist physicians concerning radiation doses and

<table>
<thead>
<tr>
<th>Diagnostic examination</th>
<th>Effective dose (mSv)</th>
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<tbody>
<tr>
<td>X-rays: Chest (PA film)</td>
<td>0.02</td>
</tr>
<tr>
<td>Limbs/joints</td>
<td>0.06</td>
</tr>
<tr>
<td>Head</td>
<td>0.07</td>
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<tr>
<td>Screening mammogram</td>
<td>0.13</td>
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<tr>
<td>Cervical spine</td>
<td>0.3</td>
</tr>
<tr>
<td>Abdomen</td>
<td>0.53</td>
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<tr>
<td>Pelvis/hip</td>
<td>0.83</td>
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<tr>
<td>Thoracic spine</td>
<td>1.4</td>
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<tr>
<td>Lumbar spine</td>
<td>1.8</td>
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<tr>
<td>Upper GI</td>
<td>3.8</td>
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<tr>
<td>Lower GI</td>
<td>6.4</td>
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<tr>
<td>CT: Head</td>
<td>2.0</td>
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<tr>
<td>Abdomen</td>
<td>10.0a</td>
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<tr>
<td>Chest</td>
<td>10–40a</td>
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<tr>
<td>Pulmonary angiography</td>
<td>20–40a</td>
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<td>PET-CT</td>
<td>25</td>
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*aCT protocols that overlap scanned regions or rescan the same anatomic region of interest, (e.g., noncontrast and contrast-enhanced scans), impart two to three times the radiation dose.

PA = postero-anterior, GI = gastrointestinal, PET = positron emission tomography.
risks (45). The results of the study revealed an urgent need to improve physicians’ understanding of radiation exposure. Only 27% of doctors attained the generous cutoff of a 45% passing mark, and only 57% of radiologists and radiology-related subspecialists passed the test.

This lack of awareness of potential radiation risks from CT is well illustrated by a recent article on lung cancer screening in a premier medical journal (46). The authors described the various benefits and drawbacks of lung-cancer screening, but made no mention of the potential risk of inducing cancer by radiation. The breach in communication has created a deficit in public awareness regarding the untoward effects of radiation doses associated with CT examinations. The obligation of physicians to provide information on diseases and the risk/benefit ratio of diagnostic procedures and treatment options has come under scrutiny in the modern medical environment. The radiology community should be committed to dose reduction, which will require a team approach involving major radiology and radiology-related groups, including radiological societies, manufacturers, standards organizations, regulators, and public agencies (43). It is also the responsibility of the radiology community to increase consumer education by describing radiation risks and alternative, safe imaging modalities. Educational efforts should be directed toward referring physicians, regulators, public health officials, and patients. Key components for ensuring patient safety include limiting the improper use of CT, and minimizing exposure to levels that are essential for achieving satisfactory image quality.

**RADIATION RISK UNCERTAINTIES**

No major scientific body that investigates radiation risks, including the International Commission on Radiological Protection (ICRP) (5), the National Academy of Sciences Committee on the Biological Effects of Ionizing Radiation (BEIR) (6), and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (7), recommends the use of a threshold dose for the induction of cancer. The Department of Health and Human Services first listed ionizing radiation as a known human carcinogen in 2005 (47). The most recent report on mortality from the Life Span Study (LSS) cohort of atom-bomb survivors followed by the Radiation Effects Research Foundation (RERF) showed that excess solid cancer risks appear to be linear in dose even for equivalent doses in the 0–150 mSv range, with no evidence for a threshold (16). In the United States, the National Council on Radiation Protection and Measurements recently concluded that “there is no conclusive evidence on which to reject the assumption of a linear-nonthreshold dose-response relationship for many of the risks attributable to low-level ionizing radiation...” (48). The results from the largest study of nuclear workers ever conducted showed that radiation risk estimates were “higher, but statistically compatible with, the risk estimates used for current radiation protection standards” (49).

The BEIR VII report recently released by the National Academy of Sciences provides the most up-to-date and comprehensive risk estimates for cancer from exposure to low-level ionizing radiation (33). The BEIR VII executive summary states that “a comprehensive review of available biological and biophysical data supports a linear-no-threshold (LNT) risk model- that the risk of cancer proceeds in a linear fashion at lower doses without a threshold and that the smallest dose has the potential to cause a small increase in risk to humans” (33). A “low dose” is defined by the BEIR VII committee as ranging from almost zero to ~100 mSv (0.1 Sv). On average, assuming an age and sex distribution similar to that of the entire U.S. population, the BEIR VII lifetime risk model predicts that approximately one individual in 1000 will develop cancer from an exposure to 10 mSv (0.01 Sv) of low-dose radiation (33). The BEIR VII report concludes by stating that future medical radiation studies are warranted, and emphasizes that “of concern for radiological protection is the increasing use of computed tomography (CT) scans and diagnostic X rays” (www.nap.edu). It is therefore clear that the carcinogenic potential of radiation at doses encountered in CT needs to be taken seriously by the medical imaging community.

Nonetheless, it is important to recognize that there are considerable uncertainties in the current radiation risk estimates as provided by organizations such as the ICRP, UNSCEAR, and BEIR, especially at the lower dose levels encountered in CT (50). The available evidence is not conclusive, primarily because of the absence of definitive epidemiological data at low dose levels. Some investigators have reviewed the available epidemiological and radiobiological evidence and concluded that the current ICRP risk estimates are too high (51–53). It has also been suggested that low-dose radiation may be beneficial, and that our concerns about the radiation risks of CT doses is unwarranted (54,55). At the same time, it is also necessary to acknowledge that some researchers have suggested that radiation risks may be even higher than those currently adopted for practical use by radiation protection bodies (56–58). Radiation risk estimates for low radiation doses are a very controversial topic, and there is currently no scientific consensus regarding the existence of any threshold dose below which the risk of cancer induction would be zero.

Given the uncertainty as to whether there is a threshold dose for radiation-induced cancer, any decision that is made may eventually turn out to be erroneous. If we assume that there are radiation risks when there are none, we will be expending efforts and resources to minimize nonexistent risks; however, if there truly are radiation risks and we choose to ignore them, we will be subjecting our patients to long-term detrimental consequences. Making decisions as to how to act in the presence of scientific uncertainty is essentially a political process, and therefore will require the use of value judgments (59).

**WHAT SHOULD BE DONE?**

In the absence of definitive evidence on the effects of low dose radiation, and a corresponding consensus in the scientific community, the prudent course of action is to act on the assumption that low-dose radiation may well
cause cancer. If we assume that CT doses may cause cancer, it would be reasonable for the radiology community to seek ways to eliminate unnecessary radiation exposure while ensuring appropriate utilization of CT. A CT examination may be considered indicated when the benefits of the CT would outweigh any assumed radiation risks. Adoption of this course of action is in no way expected to impede the undoubted benefits of CT technology for all indicated examinations. Below we describe three essential components of an effective strategy to promote patient safety and minimize any detrimental effects of CT radiation exposures.

**Consider Alternatives to CT**

Until recent times, MRI has been considered as an alternative modality to CT investigation for cases in which 1) there are contraindications to CT (e.g., allergy to contrast agents or poor renal function) or 2) the CT findings are inconclusive. However, cumulative experience has demonstrated that MRI surpasses CT in several respects:

1. MRI avoids the significant health risk associated with a radiation dose from a CT procedure. The ionizing radiation dose makes CT especially unsuitable for studies that require serial assessments in which the doses will become additive.
2. MRI provides inherently superior soft-tissue contrast even before the administration of intravenous contrast.
3. Greater patient safety is achieved with the gadolinium (Gd)-based contrast agents used in MRI compared to the iodine-based contrast agents used in CT.
4. More different types of tissue can be interrogated during a single MRI examination, and thus data reflecting a greater range of chemical and physical properties of both normal and abnormal tissue can be obtained.

The use of MRI and ultrasound eliminates exposure to the ionizing radiation encountered in CT. The existence of safe and robust imaging modalities such as MRI should obviate altogether the risk/benefit ratio invoked in many clinical scenarios involving CT use. CT should be reserved for use as a problem-solving modality only when it is clearly the superior approach. CT is indicated for the evaluation of primary lung disease (e.g., interstitial lung disease), the majority of chest and abdominal traumas, evaluation of tubes and catheters in postoperative or intensive-care patients, and identification of renal calculi (62–67). It is equally important to acknowledge the limitations of MRI in terms of both diagnostic accuracy and safety. Patients with cardiac pacemakers and ferrous intracranial vascular clips are not candidates for MRI (68), and indeed MRI has been reported to cause death in such patients (69). The known hazards associated with flying ferromagnetic objects, internal prostheses, and wire or metal objects in contact with the skin of patients can be avoided by the routine implementation of mandatory screening questionnaires filled out by patients before each MRI examination. A major current concern is that patients with chronic renal failure may develop a serious medical condition—nephrogenic systemic fibrosis (NSF)—if they receive a high dose of Gd chelate (70,71). To date, however, it appears that Omniscan™ is the contrast agent most likely to result in this condition. A prudent course of action would be to use the more stable Gd chelates—Magnevis® and MultiHance®—in all patients with renal failure.

Following the introduction of rapid high-quality scanning techniques and the development of new tissue-specific contrast agents, the application of MRI for many organ systems has achieved unprecedented growth. The majority of benign, malignant, and inflammatory diseases of the spleen, adrenals, kidneys, pancreas, and organs of the male and female pelvis are well depicted by MRI, and in the hands of experienced practitioners are better elucidated than they would be on CT (72–76). The superiority of MRI over CT for detecting and characterizing focal liver lesions and liver disease is well established (77–80). In patients with malignancy, MRI demonstrates an advantage over CT in detecting extrahepatic abdominal disease in many sites (81). Further, although MRI is acknowledged as being superior to CT for detecting disease in many individual organ systems, a recent study showed that whole-body MRI for evaluating metastatic disease was equivalent to, and in some instances more accurate than "gold standard" reference techniques such as CT (82). It is beyond the scope or the intention of this review to describe the role played by MRI in organ systems that are often studied by CT investigation. The interested reader is directed to a recent textbook on this subject (83) for further details.

Two key issues have served as impediments to a widespread preference for MRI over CT in the community: 1) health-care costs and 2) the ordering practices of referring physicians. Until recently, MRI has been considered an expensive diagnostic test. However, the actual costs of MRI equipment, service, and site expenses have plummeted over the past 20 years by factors of approximately 65%, 55%, and 80%, respectively. The average MRI technical fee in 2004 had fallen by 70% compared to the average fee in 1985. Further, the trend of decreasing costs for MRI is expected to continue over the next 20 years (84). The charges for MRI studies are generally about 20% higher than those for CT studies (hospital charges).

Changes in practice, such as eliminating inappropriate referrals for CT, will exert the most dramatic impact on avoiding the hazards of radiation but will be the most challenging to implement. A logical first step to a transition in imaging ordering patterns would be to utilize MRI as the primary imaging tool to investigate diseases of the liver. The rationale for this is fourfold: 1) the intrinsic safety of the modality, contrast agents, and intravenous injection process; 2) the established greater accuracy of MRI over CT for liver investigations (78) (Fig. 1); 3) the ease of performing MRI; and 4) the ease of interpreting MRI studies, even without extensive MR training. A number of practices by various radiology agencies would have to be modified to aid in this conversion, including recommendations by various international colleges of radiology, and increasing the con-
tent of abdominal MRI examination material on radiology certification examinations.

Use CT Only When Indicated

Due to the popularity of volumetric imaging acquisition techniques and the rapid speed at which CT images can be obtained, the utilization of CT scans has greatly increased in recent years (85). CT is responsible for the largest component of medical radiation, which is by far the largest source of man-made exposures of the population (20). Although CT in a typical U.S. hospital represents only ~10% of all x-ray imaging, the radiation from CT accounts for up to 67% of all medical radiation (20,37). CT use in the U.S. has been growing rapidly since the mid 1990s, and shows no sign of abating (44). Coexistent with the increased volume of CT exams is the growing proportion of unnecessary CT evaluations. This principle is exemplified by data gathered from a major medical center by Donnelly (85) in 2005, which indicated a 65% interval increase in pediatric abdominal CT exam referrals from the emergency department during the first quarter of the 2002 academic year compared to the same period in 2001. In this article, multiple factors were listed as contributing to the problem of unnecessary referrals for CT studies, including 1) overcautious ordering patterns of referring physicians with concerns related to potential malpractice litigation, 2) monetary incentives to perform more CT studies related to fee-for-service financial arrangements, and 3) pressure from the American public to use high-end technology. An example of a CT application that does not improve diagnostic accuracy but is being used increasingly is investigation of children with suspected appendicitis (86).

The current and ever-growing number of pediatric and adult diagnostic CTs performed in western countries annually is compounded by the increasing number of independent radiology clinics that use full-body CT screening in healthy adults. Despite the lack of supporting data for a life-prolonging benefit, CT scanning continues to be popular for screening and early detection of a variety of diseases, including coronary artery disease, lung cancer, and colon cancer (18,87). Unregulated direct-to-consumer marketing and self-referral are galvanizing this trend in CT whole-body screening (88). Self-referred diagnostic screening recently expanded to functional brain imaging using single photon emission CT (88). This form of functional CT imaging is advertised with a focus on school-aged children who are performing at marginal educational levels and adults who are concerned about memory loss (89). In advertisements for CT screening, references to the health risk of irradiation associated with CT scans are notably absent (62). In the private sector, the use of CT scanners to perform elective total-body scans and cardiac CTs is a lucrative business. Supervision of dosimetry at such scanning centers does not routinely occur (34).

Communication between health-care providers and radiologists is critical for determining whether a CT scan is appropriate. CT should only be performed when the benefit to the patient outweighs any assumed radiation risk (90). Supplied with sufficient clinical information, the radiologist may be able to suggest an acceptable alternative that does not use ionizing radiation, such as MRI or ultrasound. Dialogue between the referring physician and the radiologist is essential, especially given a generally uninformed medical community with inadequate knowledge about radiation exposure (45). With the advent of widespread hospital and clinic-based electronic medical record (EMR) systems, an effective strategy for modifying behavior and ordering practices may be to employ a decision support system. When a referring physician orders an imaging study, a computer-based decision support system would list indications for various imaging modalities and, when relevant, provide radiation dose and concomitant health risk information for CT. Additionally, there should be an automated system in place to track imaging-related radiation exposures in each patient’s EMR. This system would serve two purposes: 1) it would provide decision support for physicians ordering radiation-based imaging modalities, especially for patients with previous exposures, and 2) it would create an important database to be used in future epidemiological studies aimed at clarifying potential health risks associated with low-dose ionizing radiation.

Keep Patient Doses as Low as Reasonably Achievable (ALARA)

CT is a digital technology that suffers no obvious image quality-related penalty for high doses of radiation.
Higher CT doses enhance image quality by reducing quantum mottle, whereas in screen-film radiography higher doses result in overexposed (dark) examinations with little image contrast (20). Increasing CT radiation doses above a certain level will not contribute to improving diagnostic image quality, and will only result in depositing more radiation into the patient’s body (25,91). Maximizing image quality in this way while ignoring the patient’s exposure to radiation is inappropriate. For example, techniques that employ modern multidetector CT technology, multiphase contrast-enhanced CT of the liver or kidneys, or CT urography, are generally performed with the intention of acquiring sufficient data for maximal image quality and diagnostic information, and often not enough attention is paid to limiting radiation exposure.

An insufficient radiation dose in CT will result in increased image mottle with concomitant degradation of the radiologist’s ability to detect low-contrast lesions. Accordingly, in digital imaging modalities there is a tendency to increase the amount of radiation used to avoid this problem (dose creep) (92,93). Increasing doses in this manner does not necessarily improve diagnostic performance, but will always increase the patient dose. It is essential that the amount of radiation used to perform a CT examination is appropriately sufficient to obtain the required diagnostic performance, and that radiation exposures are kept ALARA (94). As an example, multiphase examinations comprise studies in which repeat examinations of an anatomic area are performed relative to the administration of intravenous contrast material. Precontrast studies are the most familiar, but early- (arterial), mid- (venous), and late-phase CT scans may also be performed (20). Every additional phase increases the radiation dose and risk by the multiple of the total number of phases (20). It has been reported that multiphase scanning is used for approximately 30% of pediatric patients undergoing body CT, often in three phases (39). Multiple scan protocols should be held to a minimum (90).

It is important to note that the ALARA principle is practical and can be achieved without sacrificing any of the benefits of diagnostic information that CT currently offers to medical practitioners and their patients. We illustrate this principle by considering in the following paragraphs how CT scanning that takes into account the patient size, as well as the specific diagnostic task, can reduce doses with no corresponding penalty in terms of acquired diagnostic information.

**Patient Size**

Until very recently, children and adults were routinely scanned with identical protocols that did not differentiate between the large differences in patient sizes and the corresponding differences in transmitted x-ray intensities (25). In part, this was likely a result of the fact that digital imaging systems can operate at any level of radiation exposure, and there is no corresponding image quality “penalty” associated with higher doses. Recent studies in pediatric CT have shown that it is unacceptable to use a tube current setting that is inappropriate for an adult on a child (85,95,96). Reductions in tube current or gantry speed have recently been introduced that decrease the radiation dose in pediatric CT (97–99). It is a welcome sign that most major manufacturers have recently added dose-reduction features specifically geared toward pediatric patients, and initiated user education programs for CT dose control (43). Regulatory agencies and accreditation bodies now require operators of CT scanners to employ patient size-specific technique charts (43,100). The recent emphasis of the ALARA principle in radiological practice and the corresponding dose reductions do not appear to have adversely affected CT diagnostic performance (101).

**Imaging Task**

Another key component of dose reduction is the development of CT imaging protocols that explicitly take into account the diagnostic task at hand (102). It is not prudent to set technique factors without considering the purpose of the scan, as it is often possible to significantly reduce patient doses without adversely affecting diagnostic performance. CT scanning performed after the administration of iodinated contrast agents may produce much higher contrast-to-noise ratios (CNRs) for enhancing lesions when performed at lower x-ray tube voltages (80 kV), which could offer major dose savings (103,104). CT pelvimetry is another task-dependent CT examination in which reductions of radiation dose are both essential and achievable (105,106). CT screening protocols for lung cancer frequently reduce the x-ray tube output by an order of magnitude in comparison with routine chest CT examinations, and there is no evidence of any detrimental impact of these dose reductions in terms of diagnostic performance (107,108). Many researchers are investigating ways to dramatically reduce radiation exposure while maintaining diagnostic information (109), and expanding such studies could help to significantly reduce population CT doses. Dual-source CT was recently released. In addition to providing faster imaging acquisition times and higher temporal resolution, according to its manufacturer it uses 50% less radiation exposure than traditional CT scans, which may be especially useful for cardiac imaging (110).

**CONCLUSIONS**

The fact that CT has exerted a tremendous impact on diagnostic radiology over the past few decades is undeniable. However, there is growing concern about the potential for significant health risks, on both individual and public health levels, attributable to CT radiation. Despite the diversity of opinion regarding the exact nature of the health risk, we hope there is a consensus of commitment to hold the standard of patient safety at a premium. Therefore, in this article we have attempted to give a balanced view in defining the problem and offering a practical approach to dose reduction. The information contained in this article should not be construed as an indictment of current medical practices, but rather as an incentive to increase awareness, pre-
vent unnecessary health risks, and ultimately improve patient care.

**ACKNOWLEDGMENT**

Jorge Elias, Jr., is supported by the National Council of Scientific and Technological Development of Brazil.

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