

REVIEW ARTICLE

CURRENT CONCEPTS

Computed Tomography — An Increasing Source of Radiation Exposure

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THE ADVENT OF COMPUTED TOMOGRAPHY (CT) HAS REVOLUTIONIZED diagnostic radiology. Since the inception of CT in the 1970s, its use has increased rapidly. It is estimated that more than 62 million CT scans per year are currently obtained in the United States, including at least 4 million for children.¹

By its nature, CT involves larger radiation doses than the more common, conventional x-ray imaging procedures (Table 1). We briefly review the nature of CT scanning and its main clinical applications, both in symptomatic patients and, in a more recent development, in the screening of asymptomatic patients. We focus on the increasing number of CT scans being obtained, the associated radiation doses, and the consequent cancer risks in adults and particularly in children. Although the risks for any one person are not large, the increasing exposure to radiation in the population may be a public health issue in the future.

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CT AND ITS USE

The basic principles of axial and helical (also known as spiral) CT scanning are illustrated in Figure 1. CT has transformed much of medical imaging by providing three-dimensional views of the organ or body region of interest.

The use of CT has increased rapidly, both in the United States and elsewhere, notably in Japan; according to a survey conducted in 1996,² the number of CT scanners per 1 million population was 26 in the United States and 64 in Japan. It is estimated that more than 62 million CT scans are currently obtained each year in the United States, as compared with about 3 million in 1980 (Fig. 2).³ This sharp increase has been driven largely by advances in CT technology that make it extremely user-friendly, for both the patient and the physician.

COMMON TYPES OF CT SCANS

CT use can be categorized according to the population of patients (adult or pediatric) and the purpose of imaging (diagnosis in symptomatic patients or screening of asymptomatic patients). CT-based diagnosis in adults is the largest of these categories. (About half of diagnostic CT examinations in adults are scans of the body, and about one third are scans of the head, with about 75% obtained in a hospital setting and 25% in a single-specialty practice setting.¹) The largest increases in CT use, however, have been in the categories of pediatric diagnosis^{4,5} and adult screening,⁶⁻¹³ and these trends can be expected to continue for the next few years.

The growth of CT use in children has been driven primarily by the decrease in the time needed to perform a scan — now less than 1 second — largely eliminating the need for anesthesia to prevent the child from moving during image ac-

Table 1. Typical Organ Radiation Doses from Various Radiologic Studies.

Study Type	Relevant Organ	Relevant Organ Dose* (mGy or mSv)
Dental radiography	Brain	0.005
Posterior–anterior chest radiography	Lung	0.01
Lateral chest radiography	Lung	0.15
Screening mammography	Breast	3
Adult abdominal CT	Stomach	10
Barium enema	Colon	15
Neonatal abdominal CT	Stomach	20

* The radiation dose, a measure of ionizing energy absorbed per unit of mass, is expressed in grays (Gy) or milligrays (mGy); 1 Gy = 1 joule per kilogram. The radiation dose is often expressed as an equivalent dose in sieverts (Sv) or millisieverts (mSv). For x-ray radiation, which is the type used in CT scanners, 1 mSv = 1 mGy.

quisition.⁴ The major growth area in CT use for children has been presurgical diagnosis of appendicitis, for which CT appears to be both accurate and cost-effective — though arguably no more so than ultrasonography in most cases.¹⁴ Estimates of the proportion of CT studies that are currently performed in children range between 6% and 11%.^{1,15}

A large part of the projected increase in CT scanning for adults will probably come from new CT-based screening programs for asymptomatic patients. The four areas attracting the most interest are CT colonography (virtual colonoscopy^{6,7}), CT lung screening for current and former smokers,^{8–10} CT cardiac screening,¹⁰ and CT whole-body screening.^{12,13}

RADIATION DOSES FROM CT SCANS

QUANTITATIVE MEASURES

Various measures are used to describe the radiation dose delivered by CT scanning, the most relevant being absorbed dose, effective dose, and CT dose index (or CTDI).

The absorbed dose is the energy absorbed per unit of mass and is measured in grays (Gy). One gray equals 1 joule of radiation energy absorbed per kilogram. The organ dose (or the distribution of dose in the organ) will largely determine the level of risk to that organ from the radiation. The effective dose, expressed in sieverts (Sv), is used for dose distributions that are not homogeneous (which is always the case with CT); it is designed to be proportional to a generic estimate

of the overall harm to the patient caused by the radiation exposure. The effective dose allows for a rough comparison between different CT scenarios but provides only an approximate estimate of the true risk. For risk estimation, the organ dose is the preferred quantity.

Organ doses can be calculated or measured in anthropomorphic phantoms.¹⁶ Historically, CT doses have generally been (and still are) measured for a single slice in standard cylindrical acrylic phantoms¹⁷; the resulting quantity, the CT dose index, although useful for quality control, is not directly related to the organ dose or risk.¹⁸

TYPICAL ORGAN DOSES

Organ doses from CT scanning are considerably larger than those from corresponding conventional radiography (Table 1). For example, a conventional anterior–posterior abdominal x-ray examination results in a dose to the stomach of approximately 0.25 mGy, which is at least 50 times smaller than the corresponding stomach dose from an abdominal CT scan.

Representative calculated organ doses for frequently used machine settings¹ are shown in Figure 3A and 3B for a single CT scan of the head and of the abdomen, the two most common types of CT scan. The number of scans in a given study is, of course, an important factor in determining the dose. For example, Mettler et al.¹⁵ reported that in virtually all patients undergoing CT of the abdomen or pelvis, more than one scan was obtained on the same day; among all patients undergoing CT, the authors reported that at least three scans were obtained in 30% of patients, more than five scans in 7%, and nine or more scans in 4%.

The radiation doses to particular organs from any given CT study depend on a number of factors. The most important are the number of scans, the tube current and scanning time in milliamp-seconds (mAs), the size of the patient, the axial scan range, the scan pitch (the degree of overlap between adjacent CT slices), the tube voltage in the kilovolt peaks (kVp), and the specific design of the scanner being used.¹⁷ Many of these factors are under the control of the radiologist or radiology technician. Ideally, they should be tailored to the type of study being performed and to the size of the particular patient, a practice that is increasing but is by no means universal.¹⁹ It is always the case that the relative noise in CT images will

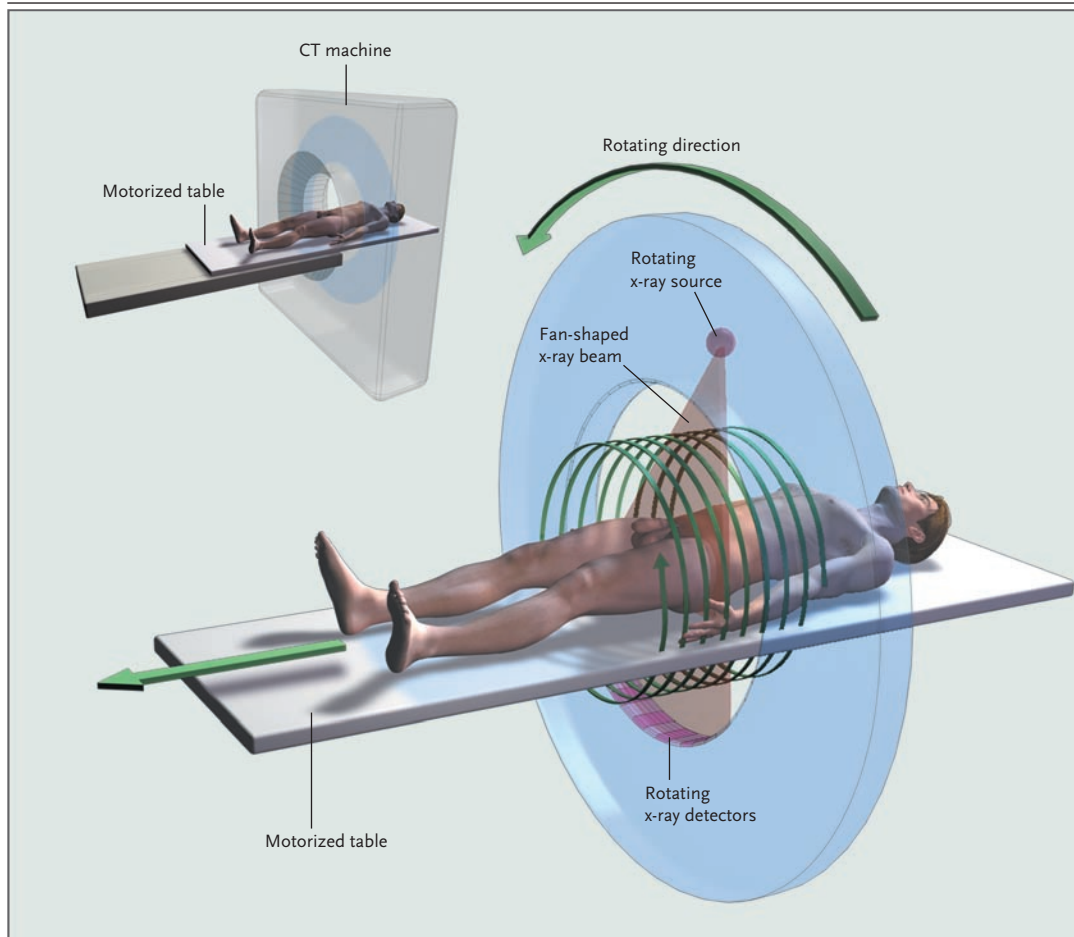


Figure 1. The Basics of CT.

A motorized table moves the patient through the CT imaging system. At the same time, a source of x-rays rotates within the circular opening, and a set of x-ray detectors rotates in synchrony on the far side of the patient. The x-ray source produces a narrow, fan-shaped beam, with widths ranging from 1 to 20 mm. In axial CT, which is commonly used for head scans, the table is stationary during a rotation, after which it is moved along for the next slice. In helical CT, which is commonly used for body scans, the table moves continuously as the x-ray source and detectors rotate, producing a spiral or helical scan. The illustration shows a single row of detectors, but current machines typically have multiple rows of detectors operating side by side, so that many slices (currently up to 64) can be imaged simultaneously, reducing the overall scanning time. All the data are processed by computer to produce a series of image slices representing a three-dimensional view of the target organ or body region.

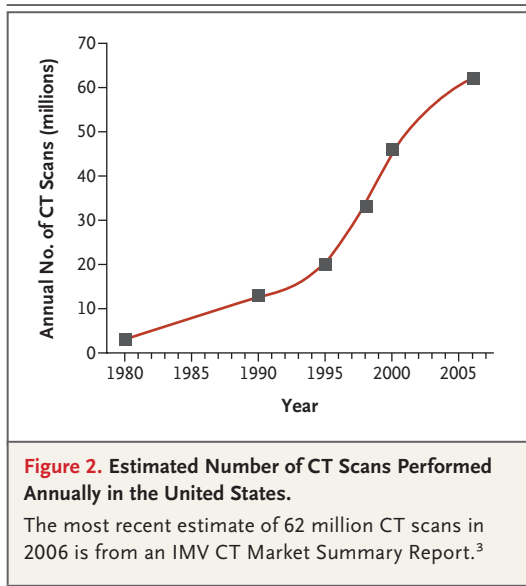
increase as the radiation dose decreases, which means that there will always be a tradeoff between the need for low-noise images and the desirability of using low doses of radiation.²²

BIOLOGIC EFFECTS OF LOW DOSES OF IONIZING RADIATION

MECHANISM OF BIOLOGIC DAMAGE

Ionizing radiation, such as x-rays, is uniquely energetic enough to overcome the binding energy of the electrons orbiting atoms and molecules; thus,

these radiations can knock electrons out of their orbits, thereby creating ions. In biologic material exposed to x-rays, the most common scenario is the creation of hydroxyl radicals from x-ray interactions with water molecules; these radicals in turn interact with nearby DNA to cause strand breaks or base damage. X-rays can also ionize DNA directly. Most radiation-induced damage is rapidly repaired by various systems within the cell, but DNA double-strand breaks are less easily repaired, and occasional misrepair can lead to induction of point mutations, chromosomal translocations, and



gene fusions, all of which are linked to the induction of cancer.²³

RISKS ASSOCIATED WITH LOW DOSES OF RADIATION

Depending on the machine settings, the organ being studied typically receives a radiation dose in the range of 15 millisieverts (mSv) (in an adult) to 30 mSv (in a neonate) for a single CT scan, with an average of two to three CT scans per study. At these doses, as reviewed elsewhere,²⁴ the most likely (though small) risk is for radiation-induced carcinogenesis.

Most of the quantitative information that we have regarding the risks of radiation-induced cancer comes from studies of survivors of the atomic bombs dropped on Japan in 1945.²⁵ Data from cohorts of these survivors are generally used as the basis for predicting radiation-related risks in a population because the cohorts are large and have been intensively studied over a period of many decades, they were not selected for disease, all age groups are covered, and a substantial sub-cohort of about 25,000 survivors²⁶ received radiation doses similar to those of concern here — that is, less than 50 mSv. Of course, the survivors of the atomic bombs were exposed to a fairly uniform dose of radiation throughout the body, whereas CT involves highly nonuniform exposure, but there is little evidence that the risks for a specific organ are substantially influenced by exposure of other organs to radiation.

There was a significant increase in the overall

risk of cancer in the subgroup of atomic-bomb survivors who received low doses of radiation, ranging from 5 to 150 mSv²⁷⁻²⁹; the mean dose in this subgroup was about 40 mSv, which approximates the relevant organ dose from a typical CT study involving two or three scans in an adult.

Although most of the quantitative estimates of the radiation-induced cancer risk are derived from analyses of atomic-bomb survivors, there are other supporting studies, including a recent large-scale study of 400,000 radiation workers in the nuclear industry^{30,31} who were exposed to an average dose of approximately 20 mSv (a typical organ dose from a single CT scan for an adult). A significant association was reported between the radiation dose and mortality from cancer in this cohort (with a significant increase in the risk of cancer among workers who received doses between 5 and 150 mSv); the risks were quantitatively consistent with those reported for atomic-bomb survivors.

The situation is even clearer for children, who are at greater risk than adults from a given dose of radiation (Fig. 4), both because they are inherently more radiosensitive and because they have more remaining years of life during which a radiation-induced cancer could develop.

In summary, there is direct evidence from epidemiologic studies that the organ doses corresponding to a common CT study (two or three scans, resulting in a dose in the range of 30 to 90 mSv) result in an increased risk of cancer. The evidence is reasonably convincing for adults and very convincing for children.

CANCER RISKS ASSOCIATED WITH CT SCANS

No large-scale epidemiologic studies of the cancer risks associated with CT scans have been reported; one such study is just beginning.³² Although the results of such studies will not be available for some years, it is possible to estimate the cancer risks associated with the radiation exposure from any given CT scan²⁰ by estimating the organ doses involved and applying organ-specific cancer incidence or mortality data that were derived from studies of atomic-bomb survivors. As discussed above, the organ doses for a typical CT study involving two or three scans are in the range in which there is direct evidence of a statistically significant increase in the risk of

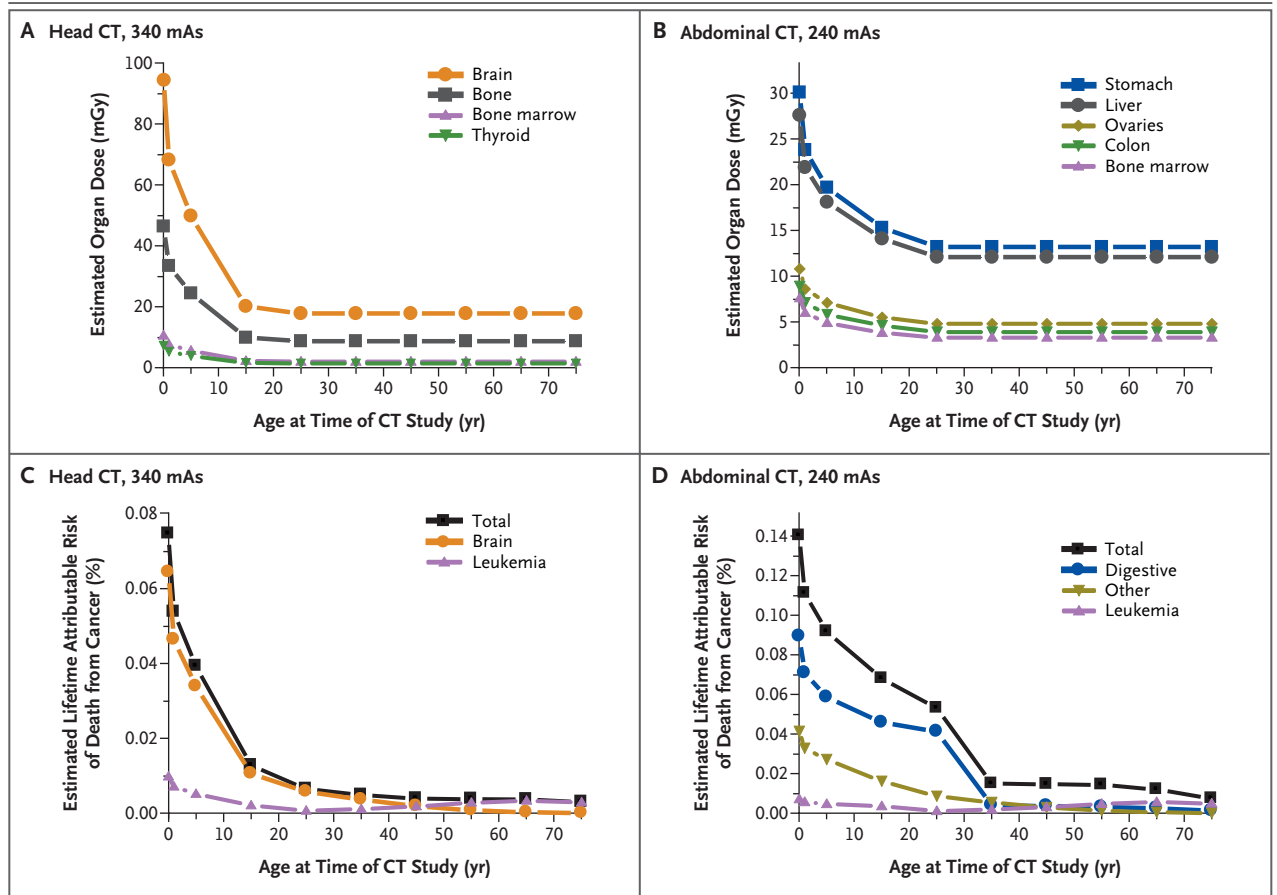


Figure 3. Estimated Organ Doses and Lifetime Cancer Risks from Typical Single CT Scans of the Head and the Abdomen.

Panels A and B show estimated typical radiation doses for selected organs from a single typical CT scan of the head or the abdomen. As expected, the brain receives the largest dose during CT of the head and the digestive organs receive the largest dose during CT of the abdomen. These doses depend on a variety of factors, including the number of scans (data shown are for a single scan) and the milliamp-seconds (mAs) setting. The data shown here refer to the median mAs settings reported in the 2000 NEXT survey of CT use.¹ For a given mAs setting, pediatric doses are much larger than adult doses, because a child's thinner torso provides less shielding of organs from the radiation exposure. The mAs setting can be reduced for children (but is often not reduced^{5,19}); a reduction in the mAs setting proportionately reduces the dose and the risk. The methods used to obtain these dose estimates have been described elsewhere,²⁰ but software that estimates organ doses for specific ages and CT settings is now generally available.²¹ Panels C and D show the corresponding estimated lifetime percent risk of death from cancer that is attributable to the radiation from a single CT scan; the risks (both for selected individual organs and overall) have been averaged for male and female patients. The methods used to obtain these risk estimates have been described elsewhere.²⁰ The risks are highly dependent on age because both the doses (Panels A and B) and the risks per unit dose are age-dependent. Even though doses are higher for head scans, the risks are higher for abdominal scans because the digestive organs are more sensitive than the brain to radiation-induced cancer.

cancer, and the corresponding CT-related risks can thus be directly assessed from epidemiologic data, without the need to extrapolate measured risks to lower doses.³³

The estimated lifetime risk of death from cancer that is attributable to a single "generic" CT scan of the head or abdomen (Fig. 3C and 3D) is calculated by summing the estimated organ-specific cancer risks. These risk estimates are based on the organ doses shown in Figure 3A and 3B,

which were derived for average CT machine settings.¹

Although the individual risk estimates shown in Figure 3 are small, the concern about the risks from CT is related to the rapid increase in its use — small individual risks applied to an increasingly large population may create a public health issue some years in the future. On the basis of such risk estimates and data on CT use from 1991 through 1996, it has been estimated that about

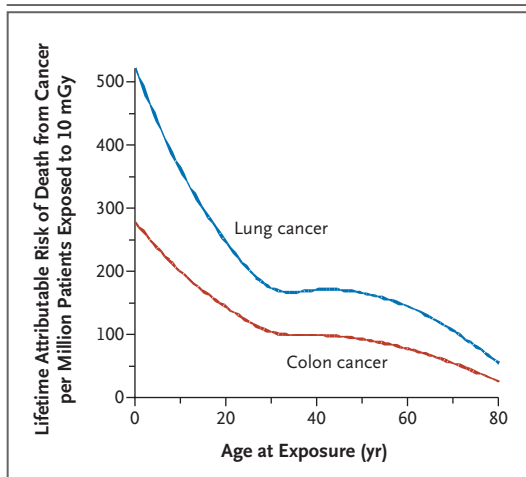


Figure 4. Estimated Dependence of Lifetime Radiation-Induced Risk of Cancer on Age at Exposure for Two of the Most Common Radiogenic Cancers.

Cancer risks decrease with increasing age both because children have more years of life during which a potential cancer can be expressed (latency periods for solid tumors are typically decades) and because growing children are inherently more radiosensitive, since they have a larger proportion of dividing cells. These risk estimates, applicable to a Western population, are from a 2005 report by the National Academy of Sciences²⁵ and are ultimately derived from studies of the survivors of the atomic bombings. The data have been averaged according to sex.

0.4% of all cancers in the United States may be attributable to the radiation from CT studies.^{2,34} By adjusting this estimate for current CT use (Fig. 2), this estimate might now be in the range of 1.5 to 2.0%.

CONCLUSIONS

The widespread use of CT represents probably the single most important advance in diagnostic radiology. However, as compared with plain-film radiography, CT involves much higher doses of radiation, resulting in a marked increase in radiation exposure in the population.

The increase in CT use and in the CT-derived radiation dose in the population is occurring just as our understanding of the carcinogenic potential of low doses of x-ray radiation has improved substantially, particularly for children. This improved confidence in our understanding of the lifetime cancer risks from low doses of ionizing radiation has come about largely because of the

length of follow-up of the atomic-bomb survivors — now more than 50 years — and because of the consistency of the risk estimates with those from other large-scale epidemiologic studies. These considerations suggest that the estimated risks associated with CT are not hypothetical — that is, they are not based on models or major extrapolations in dose. Rather, they are based directly on measured excess radiation-related cancer rates among adults and children who in the past were exposed to the same range of organ doses as those delivered during CT studies.

In light of these considerations, and despite the fact that most diagnostic CT scans are associated with very favorable ratios of benefit to risk, there is a strong case to be made that too many CT studies are being performed in the United States.^{35,36} There is a considerable literature questioning the use of CT, or the use of multiple CT scans, in a variety of contexts, including management of blunt trauma,³⁷⁻⁴⁰ seizures,⁴¹ and chronic headaches,⁴² and particularly questioning its use as a primary diagnostic tool for acute appendicitis in children.¹⁴ But beyond these clinical issues, a problem arises when CT scans are requested in the practice of defensive medicine, or when a CT scan, justified in itself, is repeated as the patient passes through the medical system, often simply because of a lack of communication. Tellingly, a straw poll³⁵ of pediatric radiologists suggested that perhaps one third of CT studies could be replaced by alternative approaches or not performed at all.

Part of the issue is that physicians often view CT studies in the same light as other radiologic procedures, even though radiation doses are typically much higher with CT than with other radiologic procedures. In a recent survey of radiologists and emergency-room physicians,⁴³ about 75% of the entire group significantly underestimated the radiation dose from a CT scan, and 53% of radiologists and 91% of emergency-room physicians did not believe that CT scans increased the lifetime risk of cancer. In the light of these findings, the pamphlet “Radiation Risks and Pediatric Computed Tomography (CT): A Guide for Health Care Providers,”⁴⁴ which was recently circulated among the medical community by the National Cancer Institute and the Society for Pediatric Radiology, is most welcome.

There are three ways to reduce the overall ra-

radiation dose from CT in the population. The first is to reduce the CT-related dose in individual patients. The automatic exposure-control option⁴⁵ on the latest generation of scanners is helping to address this concern. The second is to replace CT use, when practical, with other options, such as ultrasonography and magnetic resonance imaging (MRI). We have already mentioned the issue of CT versus ultrasonography for the diagnosis of appendicitis.¹⁴ Although the cost of MRI is decreasing, making it more competitive with CT, there are not many common imaging scenarios in which MRI can simply replace CT, although this substitution has been suggested for the imaging of liver disease.⁴⁶

The third and most effective way to reduce the

population dose from CT is simply to decrease the number of CT studies that are prescribed. From an individual standpoint, when a CT scan is justified by medical need, the associated risk is small relative to the diagnostic information obtained. However, if it is true that about one third of all CT scans are not justified by medical need, and it appears to be likely,³⁵ perhaps 20 million adults and, crucially, more than 1 million children per year in the United States are being irradiated unnecessarily.

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