

Notes to “***NEXT 2000: Survey of Computed Tomography (CT) Practice, Workload, Dose,***” by Stanley H. Stern, Ph. D., FDA/CDRH Office of Health and Industry Programs, Division of Mammography Quality and Radiation Programs, Radiation Programs Branch, to be presented to the *Technical Electronic Product Radiation Safety Standards Committee Rockville, Maryland, June 21, 2000*

Slide 1

This presentation is about how CDRH is leveraging the Nationwide Evaluation of X-Ray Trends, whose acronym is “*NEXT*,” to obtain up-to-date information on clinical practice, patient workload, and patient dose related to computed tomographic examinations and procedures across the United States:

- I will describe briefly what *NEXT* is, outline how it works, and cite some key findings.
- I’ll identify the most significant technological advances in CT since the last CT survey in 1990 and describe how innovations of this past decade and their promotion of related clinical applications have led us to revamp the CT survey.
- The heart of this discussion is the 2000-CT survey; I’ll highlight the parts of it intended to garner dose and dose-rate data associated with the most recently developed modes of operation for exams of the body as well as the head.
- A primary motivation for characterizing x-ray trends is to understand how they affect individual and population radiation dose, and so I’ll speak briefly about aspects of dosimetry that are peculiar to CT and how the survey is designed to facilitate inference of patient and population dose.
- And finally, I will mention a complementary CDRH project underway to develop a compendium of patient tissue doses associated with CT exams.

Slide 2

NEXT is a cooperative program encompassing national quality assurance and radiological-health research. The program is administered through the Conference of Radiation Control Program Directors, which is the umbrella organization of State radiation-control agency directors. CRCPD’s *NEXT* Committee coordinates annual participation of over 40 States. Each year States provide personnel who recruit clinical facilities, do on-site surveys, and perform x-ray equipment measurements in approximately 350 locations across the country—private practices, hospitals, clinics. Surveyors acquire x-ray system data on technique, exposure, image-quality, and patient-workload associated with a particular radiological examination whose selection for survey varies from year to year.

CDRH underpins the program scientifically and technically:

- We develop the survey instruments and protocols for measurement;
- We identify, design, test, procure, and calibrate equipment and materials;
- We select survey samples from State rosters of facilities;

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- We develop curricula for training surveyors;
- We enter survey results into databases, analyze, and interpret the data;
- And we publish *NEXT* findings as technical reports and as papers in peer-reviewed journals.

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The *NEXT* program is unique in the United States: It is the only mechanism for obtaining medical radiology data that are *nationally representative* of the amount x-ray exposure and numbers of people exposed, image quality, and clinical practice related to patient dose. Facilities that participate in the survey are solicited by random sampling of State rosters. What each year's survey captures for a particular type of examination are "snapshots" of the U.S. distributions of the most important machine-generated radiological variables affecting patient dose. Examples of such variables are radiation exposure at the skin-entrance plane, x-ray tube peak voltage, tube current, exposure time, x-ray spectrum half-value layer. Data have also been collected on the quality of film processing. In acquiring these data, surveyors employ patient-equivalent phantoms—some embedded with test-image objects—to attenuate the radiation. Such phantoms standardize the measurement of exposure and assessment of image quality across all facilities surveyed.

CDRH composes brochures of these data that CRCPCD provides to the States for distribution to facilities when State personnel inspect them as part of their routine radiation-control programs. These brochures serve as a quality-assurance tool: they enable comparison of the facility's radiological techniques and exposures to nationwide norms.

For a given kind of examination, national trends emerge from analysis of data collected over time. Over the course of a number of years, information published from *NEXT* surveys has proved to be a seminal resource, cited in scientific journals and used by researchers to identify radiological health problems and to suggest solutions involving changes in equipment technology, radiological techniques, and clinical protocols. In recognition of the impact of the *NEXT* program in promoting radiological health, the international journal *Applied Radiation and Isotopes* invited CDRH to review *NEXT* findings in a special edition published last year.¹

Slide 4

This slide indicates the scope and some principal findings of the *NEXT* program since 1984, and I'd like to use it to highlight several points:

- First, please look at the two columns on the left: In the past fifteen years *seven* different types of radiographic and fluoroscopic examination have been surveyed. Every few years an examination category is repeated, perhaps with some kind of variant introduced—hospitals vs. private practice, 4.7- vs. 4.2-cm compressed-breast

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phantom, adult vs. pediatric chest radiography—in order to keep pace with technological and clinical developments. In 1996, for example, along with the survey listed here for upper gastrointestinal fluoroscopy, there were pilot studies of fluoroscopy in cardiac catheterization labs and on mobile C-arm units. These kinds of technical pilots are useful as an “avant-garde” anticipating prospective widespread incorporation of such modalities into clinical practice.

- The two columns on the right correspond to measures of radiation levels, either at skin-entrance² or absorbed by the tissue of clinical interest.³ So for mammography surveys,^{4, 6, 9} the radiosensitive tissue is the glandular breast tissue, and the circled values show a clear trend of increasing mean glandular-tissue dose. Let me hasten to add that along with an increasing dose for film/screen mammography there are associated trends, which are not explicitly presented in this table, of progressively better scores for visualizing test-image objects, of the near disappearance of Xero-mammography as a relatively high-dose modality, and of the nearly universal adoption of the use of grids to suppress radiation scatter.⁶ For mammography, the bottom line is improved image quality over this period of time.
- For this slide, the last item I want to cover is computed tomography, and the CT surveys are highlighted in yellow.^{5,7} There are *two* key ideas presented here: First, skin-entrance dose (41 mGy) or internal-head dose (47 mGy) incurred on average by a patient in a routine CT head examination is the *largest dose* among those of all the radiographic exams listed, fluoroscopy^{7, 8} excluded. In fact CT may be the single modality which contributes most to the collective population x-ray dose arising from diagnostic radiological exams,¹⁰ and we are hoping that the year 2000 survey will enable estimation of just what the CT contribution is to population dose.

For CT, the numbers in parentheses are the extrema of a range that includes 50% of all of the values of the sample distribution. In other words, 50% of the doses fall within this range, and 50% fall outside of the range. The second key idea then, is that the ranges are relatively *broad*. The implication is that through judicious selection of technique factors, it's possible to obtain satisfactory image quality and spare patient dose as well.⁵ So, these two points—large dose, broad range—represent our baseline for CT.

If this is our baseline, our starting point, what are the challenges we face in mounting a survey in the year 2000? What's happened since 1990 that we need to capture in a new survey?

Slide 5

The bulleted items correspond to the principal technological advances that have already been incorporated or are being incorporated into most CT systems in the field. They have led to profound changes in how CT is applied in clinical practice:

- Slip rings are housed in the gantries of CT systems, and they conduct electrical energy between the high-voltage power supply and the rotating x-ray tube or between the computer and the data-acquisition array (if the x-ray detectors are rotating with the tube). This technology is in common use in low-cost as well as top-of-the-line scanners.¹¹

Here's the important point: Slip rings eliminate the constraint of electrical cables, and so the x-ray tube or detectors can rotate continuously—over many 360° revolutions—while the x-ray tube is energized. The technology has fostered a new mode of CT scanning referred to as “helical” or “spiral” scanning, where the patient table moves at a constant rate while the x-ray tube is rotating, and in effect the x-ray beam traces out a helical pattern around a patient as the patient table advances through the gantry opening. Helical scanning has spawned an explosion of new clinical applications of CT because of the advantages it holds over conventional, slice-by-slice, axial scanning, namely, speed, reduction of patient-motion artifacts, and facilitation volume rendering of images. Just a few examples of such applications are spiral CT angiography,^{12, 13} detection of spine fractures,¹⁴ evaluation of laryngeal disease,¹⁵ cinematically displayed visualization of pancreatic vascular and ductal anatomy,¹⁶ detection and management of renal and ureteral calculi,¹⁷ and there are many other applications. One of the key objectives of this survey is to find out what percentage of CT systems in the field have helical-scanning capability.

- Another significant advance in CT technology has been the development of high heat-capacity x-ray tubes. If we look for example at the x-ray tube specifications of one particular CT manufacturer, from 1986 to 1998 the heat capacity of their tubes increased by a factor of five, from 1.5 to 7.5 million heat units.¹⁸ This capacity in conjunction with the ability of scanners to rotate continuously has led to the growth of what's called “CT fluoroscopy.”¹⁹⁻²¹ Manufacturers also refer to this mode as “dynamic scanning” or “continuous scanning.” In this mode of operation, the x-ray source rotates continuously around the patient multiple times—in some systems up to 200 revolutions of 360° each. Contrary to the helical scanning movement, in CT fluoroscopic mode, table movement is *not* programmed to advance automatically, but it is under the control of the operator. The patient and table may stay fixed in place as the x-ray tube is activated and rotates continuously to enable low-resolution CT images to be acquired nearly in real time, at rates of 6 to 8 frames per second. The images are continuously reconstructed and displayed on a monitor typically located near the patient table. The mode is used to visualize interventional procedures involving biopsies or drainage.²⁷⁻²⁹

Last year Captain Robert Gagne addressed this Committee about FDA concerns for potentially large skin-dose and injury from CT fluoroscopy,²¹ and this year the NEXT survey has begun to obtain an accurate picture of the nationwide prevalence of this mode and the dose rates and doses associated with its use.

- A third major group of technological advances falls into a category that may be characterized as “ultra-fast” scanning. There are really two different technologies here: First “e-beam” CT refers to electron-beam computed tomography. Although it has really been around since the early 1980s,²² it wasn’t followed at all in the 1990 CT survey. In electron-beam CT, x-rays are produced by electromagnetically scanning an electron beam about a large, semicircular tungsten target underneath the patient; because there is no mechanical motion, scan times of 50 millisecond are possible.²² The extent to which electron-beam CT has caught on is not clear, and the NEXT survey is trying to answer this question.

The second technology—multi-slice helical CT—is relatively more recent.²³ It uses two to four parallel arcs of detectors to produce a double or quadruple helix of volumetric data.^{23,24} Some multi-slice scanners have x-ray tubes that spin at two revolutions per second, so that the 4-slice units can be eight times faster than most single-slice scanners.²³

Slide 6

The single word that summarizes these changes is “complexity.” Because of these developments, there has been a shift in the types of exams done: these days there are more clinical applications of CT to the body than there are to the head. In 1983, 63% of the 5 to 5.5 million CT procedures in the U.S. were head scans,²⁵ whereas a study in 1997 of the ten most frequently performed CT procedures at the Cleveland Clinic Foundation indicates that head procedures account for only 41% of the total.²⁶ Because of the advent of CT fluoroscopy, computed tomography is used to visualize interventional procedures as well as for diagnosis.²⁷⁻²⁹ The proliferation of helical scanning, with many different kinds of models and options such as CT fluoroscopy and multi-slice scanning has resulted in a variety of different irradiation and scanning conditions whose terminology itself is not completely standardized.^{23, 30} This complexity has led us to try some major changes³¹ in conducting the year-2000 CT survey compared to what was done in 1990.

Slide 7

The national sample size was initially set for 350 facilities randomly distributed across the United States. This year 42 States are actually participating in the survey, and they will cover 314 facilities. Facilities are picked randomly from rosters submitted by States, and the sample size within each State is proportional to its population. The target in each of these facilities is the most frequently used CT system.

Because of the advances in technology and clinical practice since 1990, we’ve had to introduce several new aspects into the way the NEXT survey is conducted. The major innovation is that the survey for each facility is divided into *two* parts. One part is an on-site visit that focuses on routine exams of the adult head. Even though the focus is the head exam, several crucial features of the survey pertain to body exams also. A second part of the survey is based on a questionnaire that the facility fills out in advance of the

surveyor visit. It is through this questionnaire that we hope to obtain more complete information about exams of the body, which, as I mentioned earlier, comprise the preponderant²⁶ part of the of CT universe.

This slide summarizes the important elements of the surveyor's visit on site at a participating facility. The on-site visit represents the traditional way a NEXT survey is done: a surveyor interviews a CT technologist familiar with the system and makes measurements with a standardized reference phantom. But there are several new twists as well:

- For example, we are going to determine what percentages of CT systems are capable of helical scanning and of CT fluoroscopy. Helical scanning wasn't even covered at all in the 1990-CT survey.

Also, we will obtain information about CT fluoroscopy that will help us make informed regulatory decisions. The patient-workload data and technique factors sought for the CT fluoroscopy mode are not limited to head exams: they refer to the most typically-used settings for body or head scanning for all patients—pediatric as well as adult. We are explicitly asking for the average “beam-on” time for CT fluoroscopically-guided procedures, and by making measurements of the dose, duration of exposure, and slice width near the surface of a head phantom, we can estimate the skin-dose rate and typical values of skin dose in the CT fluoroscopic mode of operation. This information will give CDRH the most definitive insight to date on the pervasiveness and dosimetry for an increasingly popular mode of operation potentially associated with skin injury.

- For the routine head exam in particular, surveyors are asking for the weekly patient workload and also for a breakdown of how a facility does those exams according to what clinical protocol. What percentage of exams involves axial CT exclusively? What percentage uses helical scanning? How many head exams consist of a scanning phase without contrast media followed by a scanning phase with contrast media? Of course, if there were two distinct phases to an examination—first without contrast then with contrast—the radiation dose would be double that for a single phase.
- We will find out the technique sets—tube voltage, current, scan time, number of slices, slice width, table increment, number of scanner rotations, and so on—applied for the most frequently used axial-scanning protocol and separately for the most frequently used helical-scanning protocol of the head.
- The survey entails three sets of exposure measurements, two of which are with the standard head phantom developed by CDRH. The head phantom is a 16-cm diameter cylinder approximately 16 cm long, made of polymethyl methacrylate, a material whose atomic composition and density make for reasonably good simulations of the radiation-scattering and attenuation properties of tissue.

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The first set of measurements will be made with an ionization chamber in the center hole of the phantom and will yield the multiple-scan average dose, abbreviated “MSAD,” which is a descriptor of the central dose amongst a series of scans comprising a head exam. These values can be directly compared to those obtained from the 1990 survey, and they will offer the clearest indication of dose trend over this past decade.

The second set of measurements will be made in a phantom hole located 1 cm from the phantom-entrance surface, and values from these measurements can be used to describe the average dose rate and dose at the skin surface when the CT unit operates in a CT fluoroscopic mode. These measurements can also be related to those obtained in the 1985 survey whose values were also measured in a surface hole of the head phantom.

The third set of measurements will have the ionization chamber aligned along the axis of rotation *free-in-air*. The great advantage of this last set of measurements is that because they are unencumbered by the attenuation and scattering introduced by the head phantom, the free-in-air values are not limited to descriptors of head dose. Free-in-air values can be applied to make estimates of internal-tissue doses to the *body* based on computer calculations by the National Radiological Protection Board of the United Kingdom.³² The NRPB calculations simulate radiation transport in an anthropomorphically modeled mathematical phantom.³² They offer a way for us to estimate what we expect will be the largest contribution to population dose from CT as it is practiced today, namely, doses to tissues from exams of the *body* not limited exclusively to exams of the head.

Slide 8

Most of this slide summarizes features of the second principal aspect of the year-2000 CT survey. The second part consists of a detailed questionnaire addressed primarily to the CT technologist but also to the medical physicist most familiar with the most frequently used CT unit. These questions cover exams of the body as well as those of the head, and although the focus is adult patients, there are some queries about pediatric patient workload and techniques too.

- First, we try to identify the types and numbers of CT units available at each facility surveyed—units with only axial-scanning capability, units that can do single-slice or multi-slice helical scanning, units capable of doing electron-beam CT.
- Second, we seek detailed enumeration of patient workload per week, of frequency of use of scanning protocols—axial *vs.* helical, contrast *vs.* no-contrast phases—and of x-ray system technique factors. Each data set is associated with an examination category for the most frequent types of examinations—abdomen and pelvis, head,

simple sinus, chest-abdomen-pelvis, and so on. This information represents the core of CT practice and exposure as they relate to patient dose in the U.S., and its acquisition would enable a detailed estimation of population dose heretofore unavailable.

- Third, the questionnaire includes a group of queries about system maintenance and quality-assurance tests. Quality assurance is an important aspect of maintaining imaging integrity and radiological protection, and it simply was not covered in the previous CT survey.

At the bottom of the slide I have underlined a major initiative intended to help the *NEXT* program transition to an era of electronic file transmission. For the first time, surveyors are being provided with diskettes containing pre-formatted spreadsheets for their data entry. We are encouraging electronic transmission of these files as a time-saving efficiency, and in the future we are planning to work with the Conference of Radiation Control Program Directors to establish web-based data entry of *NEXT* survey results.

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Previous CT surveys relied on what are called “dose descriptors” to characterize an amount of radiation energy representative of what’s absorbed per mass of generic tissue during a typical exam of the adult head. The best known dose descriptors for CT are the *multiple-scan average dose*, abbreviated “MSAD,” which I mentioned earlier, and a related quantity called the *computed tomography dose index*, abbreviated “CTDI.”^{2, 3, 5, 7} These descriptors are derived from measurements of dose within a physical phantom intended to approximate the radiation scattering and attenuation qualities of the head. (Incidentally, there is also a 32-cm diameter CT phantom that can be used for the indication of body dose.) The year-2000 CT survey will obtain measures of MSAD using a head phantom.

But what we are *really* interested in is estimating doses to the radiosensitive tissues of the body. Evaluation of tissue dose is the foundation of ionizing radiation risk assessment, and the principal risks associated with absorbed radiation are morbidity and mortality of induced cancer, transmission of genetic defects, fetal mental retardation, and acute skin injury.^{33, 34} This slide³⁴ is meant to illustrate several considerations involved in CT tissue dosimetry. What’s plotted is a single set of calculated dose values corresponding to one particular grouping of scanners—the GE series 8800 and 9000—modeled by the National Radiological Protection Board in computer simulations of radiation transport through an anthropomorphic phantom.³² The ordinate corresponds to the doses to the tissues indicated, that is, any particular color indicates the dose to the *whole* tissue, the dose averaged over the *entire mass* of the tissue wherever it’s distributed. Tissue dose is plotted as a function of the *location* of a 5-mm wide scan-slice along the length of a person. “Zero centimeters” here corresponds to the base of the trunk, and “94 centimeters” corresponds to the top of the head. In other words, if there were a single

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axial scan 50 cm above the base of the trunk, then the average dose to the breasts would be 0.015 relative units, to the lungs 0.007 units, and to the active bone marrow 0.002 units. There are two points I want to make:

- First, the unit of measure indicated by the ordinate is not tissue dose *per se*; it is actually a *ratio* of tissue dose to dose free in air. In other words, internal tissue doses are represented by ratios *normalized* to the radiation output of the CT unit so that the doses themselves can be evaluated only if one knows how much radiation the CT unit emits in the first place. This situation reflects several important facts that many people are not aware of: Internal-tissue doses *cannot be practicably measured*; they are generally *not known* during the actual radiological exam; but they can be estimated from *computer simulations*. The radiation output of a CT unit—evaluated in terms of dose free-in-air—is really just the *starting point* in the estimation of internal-tissue doses.
- Second, the radiosensitive tissues are distributed throughout body, and in order to estimate tissue doses we would need to know the anatomical ranges covered by various scanning protocols. The year-2000 survey is obtaining this information, as well as x-ray technique factors, dose free in air, exam frequency, frequency of use of contrast phases, and patient workload—hopefully all of the ingredients that we need to infer population dose from CT.

Slide 10

Finally, I would like briefly to mention a CDRH project that is complementary to the *NEXT* program CT survey, and that is the development of a handbook of tissue-dose values from CT examinations.^{33,34} The handbook will be targeted to medical physicists and radiologists in a format entailing look-up of dose values according to the type of examination. We will try to have a generally applicable set of tables—one table for each kind of exam, and that table should be valid for any CT model. We would like to include options for estimating dose for all the current and upcoming CT technologies, including multi-slice helical scanning and fluoroscopic CT as well as axial scanning. *NEXT* survey results will give us insight into how to accurately parameterize dose values in terms of these new scanning modalities. We also want to include ways to estimate pediatric and fetal doses.

Our initial approach³⁵ in handbook development is to characterize and generalize the existing data set of normalized CT doses computed by the National Radiological Protection Board of the United Kingdom.³² We have already mapped anatomical scanning regions to corresponding mathematical coordinates of the NRPB anthropomorphic phantom for approximately 50 distinct CT exams. In addition to dose free-in-air, we would like to normalize tissue doses to a reference parameter commonly measured in the U.S., namely, the computed tomography dose index. Our goal is to have this handbook available in approximately one year.

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That completes this talk. It was presented for your information, and I would be pleased to address any questions that you may have.

Cited references and notes

1. The table slide 3 has been adapted from Orhan H. Suleiman, Stanley H. Stern, and David C. Spelic, "Patient dosimetry activities in the United States: the Nationwide Evaluation of X-Ray Trends (NEXT) and tissue dose handbooks," *Applied Radiation and Isotopes*, Vol. 50, No. 1, pp. 247-259 (January 1999).

2. For all examinations except Head CT, the air kerma is determined from measurements made free in air at the skin-entrance plane. For the 1985 Head CT survey, values cited in this column correspond to the mean multiple-scan average dose (MSAD), which is the average dose at the middle of a series of scans comprising (in this case) a head exam, inferred from measurements made with a pencil ionization chamber in the **top-surface hole** of CDRH head phantoms (*cf.* ref. 5). Values in parentheses correspond to the range of the distribution including 50% of sampled values. The quantity MSAD is discussed by Thomas B. Shope, Robert M. Gagne, and Gordon C. Johnson, "A method for describing the doses delivered by transmission x-ray computed tomography," *Medical Physics* Vol. 8, No. 4, pp. 488-495 (July/August 1981). For the fluoroscopy surveys, the values cited in this column correspond to the air kerma *rate* (free in air).

3. For mammography surveys, the tissue dose is the mean glandular dose inferred from measured values of free-in-air skin-entrance air kerma applied to simulations of radiation-transport through a mathematical phantom modeled with a uniform distribution of 50% glandular tissue (by weight) and 50% adipose tissue (by weight). For the 1990 Head CT survey, values cited in this column correspond to the mean MSAD (and range of the distribution including 50% of sampled values) inferred from measurements made with a pencil ionization chamber in the **central, interior hole** of CDRH head phantoms (*cf.* ref. 7).

4. The 1985 mammography surveys used a physical phantom to represent the x-ray attenuation of a breast compressed to a uniform thickness of **4.7 cm**. See Burton J. Conway, *Nationwide Evaluation of X-Ray Trends (NEXT) Tabulation and Graphical Summary of Surveys 1984 through 1987*, CRCPD Publication 89-3, Conference of Radiation Control Program Directors, Inc., Frankfort, Kentucky, August 1989.

5. The 1985 survey was an independent project organized by CDRH and the National Cancer Institute, and it was conducted by 26 States, not part of the NEXT program. That survey did not use a randomly selected sample, but the sample size of 250 facilities was approximately the same as that used in the 1990 NEXT CT survey (*cf.* ref. 7). The 1985 values of "air kerma" are actually values of the MSAD, but they are inferred from

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measurements made with a pencil ionization chamber in the *top-surface hole*, that is, near the skin surface, of a CDRH head phantom. The MSAD value cited has been adapted from John L. McCrohan, Jack F. Patterson, Robert M. Gagne, and Howard A. Goldstein, "Average Radiation Doses in a Standard Head Examination for 250 CT Systems," *Radiology* Vol. 163, No. 1, pp. 263-268 (April 1987).

6. The 1988, 1992, and 1997 mammography surveys used a physical phantom to represent the x-ray attenuation of a breast compressed to a uniform thickness of **4.2 cm**. See Burton J. Conway, *Nationwide Evaluation of X-Ray Trends (NEXT) Tabulation and Graphical Summary of 1988 Mammography Survey*, CRCPD Publication 90-7, Conference of Radiation Control Program Directors, Inc., Frankfort, Kentucky, October 1990; Burton J. Conway, *Nationwide Evaluation of X-Ray Trends (NEXT) Tabulation and Graphical Summary of 1992 Mammography Survey*, CRCPD Publication 95-2, Conference of Radiation Control Program Directors, Inc., Frankfort, Kentucky, March 1995; Orhan H. Suleiman, David C. Spelic, John L. McCrohan, Gordon R. Symonds, and Florence Houn, "Mammography in the 1990s: The United States and Canada," *Radiology* Vol. 210, No. 2, pp. 345-351 (February 1999).

7. For the 1990-CT head exam, the "tissue dose" is actually the MSAD inferred from values measured with a pencil ionization chamber in the *central, interior hole* of the phantom. The MSAD value cited has been adapted from the CT results of Burton J. Conway, *Nationwide Evaluation of X-Ray Trends (NEXT) Summary of 1990 Computerized Tomography Survey and 1991 Fluoroscopy Survey*, Conference of Radiation Control Program Directors, CRCPD Publication 94-2, Frankfort, Kentucky, January 1994. Also see Burton J. Conway *et al.*, "Average Radiation Dose in Standard CT Examinations of the Head: Results of the 1990 NEXT Survey," *Radiology* Vol. 184, No. 1, pp. 135-140 (July 1992).

8. The 1996 fluoroscopy air-kerma rate cited comes from a preliminary data analysis presented by David Spelic and Jack Ferruolo, "1996 NEXT Fluoroscopy Survey," *Annual Meeting of the Conference of Radiation Control Program Directors*, Tacoma, Washington, May 1997.

9. The 1997 mammography data were obtained from inspections conducted under the *Mammography Quality Standards Act*.

10. Data from the United Kingdom have indicated that computed tomography is "the most significant source of exposure to diagnostic X-rays for the UK population..." See P.C. Shrimpton, D. Hart, B.F. Wall, and K. Faulkner, *Survey of CT Practice in the UK Part 1: Aspects of Examination Frequency and Quality Assurance*, NRPB-R248, National Radiological Protection Board, Chilton, Didcot, Oxon, p. 1, December 1991; Paul C. Shrimpton, "Computed Tomography—A Spiralling Challenge in Radiological Protection," in *Current Topics in Radiography Number 2*, edited by Audrey Paterson and Richard Price, (W.B. Saunders Company Ltd., London, 1996), pp. 26-34; P.C. Shrimpton

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16. Vincent M. Bonaldi *et al.*, "Helical CT of the Pancreas: A Comparison of Cine Display and Film-Based Viewing," *American Journal of Roentgenology* Vol. 170, No. 2, pp. 373-376 (February 1998).

17. Glenn M. Preminger *et al.*, "Urolithiasis: Detection and Management with Unenhanced Spiral CT—A Urologic Perspective," *Radiology* Vol. 207, No. 2, pp. 308-309 (1998).

18. Compare *Whole Body CT Scanner Model TCT-400S*, Toshiba Product Data No. 2N20108, 86-8-AC/A, Toshiba Corporation, Tokyo, Japan, 1986 to *Half-Second Helical CT Scanner Aquilion*, Toshiba Product Data No. MPDCT0122EAB, 99-01 TME/SB, Toshiba Corporation, Tokyo, Japan, 1998. For general information on CT x-ray tube technology, see Stanley H. Fox, "CT Tube Technology," in *Medical CT and Ultrasound: Current Technology and Applications*, *op. cit.*, pp. 349-357.

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22. Cynthia H. McCollough, "Principles and Performance of Electron Beam CT," in *Medical CT and Ultrasound: Current Technologies and Applications, op. cit.*, pp. 411-436.
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