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Standard Guide for Computed Tomography (CT) Imaging[1]

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1. Scope

1.1 Computed tomography (CT) is a radiographic method that provides an ideal examination technique whenever the primary goal is to locate and size planar and volumetric detail in three dimensions. Because of the relatively good penetrability of X rays, as well as the sensitivity of absorption cross sections to atomic chemistry, CT permits the nondestructive physical and, to a limited extent, chemical characterization of the internal structure of materials. Also, since the method is X-ray based, it applies equally well to metallic and nonmetallic specimens, solid and fibrous materials, and smooth and irregularly surfaced objects. When used in conjunction with other nondestructive evaluation (NDE) methods, such as ultrasound, CT data can provide evaluations of material integrity that cannot currently be provided nondestructively by any other means.

1.2 This guide is intended to satisfy two general needs for users of industrial CT equipment: (*1*) the need for a tutorial guide addressing the general principles of X-ray CT as they apply to industrial imaging; and (*2*) the need for a consistent set of CT performance parameter definitions, including how these performance parameters relate to CT system specifications. Potential users and buyers, as well as experienced CT inspectors, will find this guide a useful source of information for determining the suitability of CT for particular examination problems, for predicting CT system performance in new situations, and for developing and prescribing new scan procedures.

1.3 This guide does not specify test objects and test procedures for comparing the relative performance of different CT systems; nor does it treat CT inspection techniques, such as the best selection of scan parameters, the preferred implementation of scan procedures, the analysis of image data to extract densitometric information, or the establishment of accept/reject criteria for a new object.

1.4 Standard practices and methods are not within the purview of this guide. The reader is advised, however, that examination practices are generally part and application specific, and industrial CT usage is new enough that in many instances a consensus has not yet emerged. The situation is complicated further by the fact that CT system hardware and performance capabilities are still undergoing significant evolution and improvement. Consequently, an attempt to address generic examination procedures is eschewed in favor of providing a thorough treatment of the principles by which examination methods can be developed or existing ones revised.

1.5 The principal advantage of CT is that it nondestructively provides quantitative densitometric (that is, density and geometry) images of thin cross sections through an object. Because of the absence of structural noise from detail outside the thin plane of inspection, images are much easier to interpret than conventional radiographic data. The new user can learn quickly (often upon first exposure to the technology) to read CT data because the images correspond more closely to the way the human mind visualizes three-dimensional structures than conventional projection radiography. Further, because CT images are digital, they may be enhanced, analyzed, compressed, archived, input as data into performance calculations, compared with digital data from other NDE modalities, or transmitted to other locations for remote viewing. Additionally, CT images exhibit enhanced contrast discrimination over compact areas larger than 20 to 25 pixels. This capability has no classical analog. Contrast discrimination of better than 0.1 % at three-sigma confidence levels over areas as small as one-fifth of one percent the size of the object of interest are common.

1.6 With proper calibration, dimensional inspections and absolute density determinations can also be made very accurately. Dimensionally, virtually all CT systems provide a pixel resolution of roughly 1 part in 1000 (since, at present, 1024×1024 images are the norm), and metrological algorithms can often measure dimensions to one-tenth of one pixel or so with three-sigma accuracies. For small objects (less than 4 in. in diameter), this translates into accuracies of approximately 0.1 mm (0.003 to 0.005 in.) at three-sigma. For much larger objects, the corresponding figure will be proportionally greater. Attenuation values can also be related accurately to material densities. If details in the image are known to be pure homogeneous elements, the density values may still be sufficient to identify materials in some cases. For the case in which no *a priori* information is available, CT densities cannot be

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[1] This guide is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.01 on Radiology (X and Gamma) Method.

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used to identify unknown materials unambiguously, since an infinite spectrum of compounds can be envisioned that will yield any given observed attenuation. In this instance, the exceptional density sensitivity of CT can still be used to determine part morphology and highlight structural irregularities.

1.7 In some cases, dual energy (DE) CT scans can help identify unknown components. DE scans provide accurate electron density and atomic number images, providing better characterizations of the materials. In the case of known materials, the additional information can be traded for improved conspicuity, faster scans, or improved characterization. In the case of unknown materials, the additional information often allows educated guesses on the probable composition of an object to be made.

1.8 As with any modality, CT has its limitations. The most fundamental is that candidate objects for examination must be small enough to be accommodated by the handling system of the CT equipment available to the user and radiometrically translucent at the X-ray energies employed by that particular system. Further, CT reconstruction algorithms require that a full 180 degrees of data be collected by the scanner. Object size or opacity limits the amount of data that can be taken in some instances. While there are methods to compensate for incomplete data which produce diagnostically useful images, the resultant images are necessarily inferior to images from complete data sets. For this reason, complete data sets and radiometric transparency should be thought of as requirements. Current CT technology can accommodate attenuation ranges (peak-to-lowest-signal ratio) of approximately four orders of magnitude. This information, in conjunction with an estimate of the worstcase chord through a new object and a knowledge of the average energy of the X-ray flux, can be used to make an educated guess on the feasibility of scanning a part that has not been examined previously.

1.9 Another potential drawback with CT imaging is the possibility of artifacts in the data. As used here, an artifact is anything in the image that does not accurately reflect true structure in the part being inspected. Because they are not real, artifacts limit the user's ability to quantitatively extract density, dimensional, or other data from an image. Therefore, as with any technique, the user must learn to recognize and be able to discount common artifacts subjectively. Some image artifacts can be reduced or eliminated with CT by improved engineering practice; others are inherent in the methodology. Examples of the former include scattered radiation and electronic noise. Examples of the latter include edge streaks and partial volume effects. Some artifacts are a little of both. A good example is the cupping artifact, which is due as much to radiation scatter (which can in principle be largely eliminated) as to the polychromaticity of the X-ray flux (which is inherent in the use of bremsstrahlung sources).

1.10 Because CT scan times are typically on the order of minutes per image, complete three-dimensional CT examinations can be time consuming. Thus, less than 100 % CT examinations are often necessary or must be accommodated by complementing the inspection process with digital radiographic screening. One partial response to this problem is to use large slice thicknesses. This leads to reduced axial resolution and can introduce partial volume artifacts in some cases; however, this is an acceptable tradeoff in many instances. In principle, this drawback can be eliminated by resorting to full volumetric scans. However, since CT is to a large extent technology driven, volumetric CT systems are currently limited in the size of object that can be examined and the contrast of features that can be discriminated.

1.11 Complete part examinations demand large storage capabilities or advanced display techniques, or both, and equipment to help the operator review the huge volume of data generated. This can be compensated for by stateof-the-art graphics hardware and automatic examination software to aid the user. However, automated accept/reject software is object dependent and to date has been developed and employed in only a limited number of cases.

1.12 The values stated in SI units are to be regarded as the standard. The values given in parentheses are provided for information only.

1.13 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 1316 Terminology for Nondestructive Examinations[2]

E 1570 Practice for Computed Tomographic (CT) Examination[2]

3. Terminology

3.1 *Definitions*—CT, being a radiographic modality, uses much the same vocabulary as other X-ray techniques. A number of terms are not referenced, or are referenced without discussion, in Terminology E 1316. Because they have meanings or carry implications unique to CT, they appear with explanation in Appendix X1. Throughout this guide, the term "X-ray" is used to denote penetrating electromagnetic radiation; however, electromagnetic radiation may be either X rays or gamma rays.

3.2 *Acronyms:Acronyms:*

3.2.1 *BW*—beam width.

3.2.2 *CDD*—contrast-detail-dose.

3.2.3 *CT*—computed tomography.

3.2.4 *CAT*—computerized axial tomography.

3.2.5 *DR*—digital radiography.

3.2.6 *ERF*—edge response function.

3.2.7 *LSF*—line spread function.

3.2.8 *MTF*—modulation transfer function.

3.2.9 *NDE*—nondestructive evaluation.

3.2.10 *PDF*—probability distribution function.

3.2.11 *PSF*—point spread function.

4. Summary of Guide

4.1 This guide provides a tutorial introduction to the technology and terminology of CT. It deals extensively with the

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[2] *Annual Book of ASTM Standards*, Vol 03.03.

physical and mathematical basis of CT, discusses the basic hardware configuration of all CT systems, defines a comprehensive set of fundamental CT performance parameters, and presents a useful method of characterizing and predicting system performance. Also, extensive descriptions of terms and references to publications relevant to the subject are provided.

4.2 This guide is divided into three main sections. Sections 5 and 6 provide an overview of CT: defining the process, discussing the performance characteristics of CT systems, and describing the basic elements of all CT systems. Section 8 addresses the physical and mathematical basis of CT imaging. Section 8 addresses in more detail a number of important performance parameters as well as their characterization and verification. This section is more technical than the other sections, but it is probably the most important of all. It establishes a single, unified set of performance definitions and relates them to more basic system parameters with a few carefully selected mathematical formulae.

5. Significance and Use

5.1 This guide provides a tutorial introduction to the theory and use of computed tomography. This guide begins with a overview intended for the interested reader with a general technical background. Subsequent, more technical sections describe the physical and mathematical basis of CT technology, the hardware and software requirements of CT equipment, and the fundamental measures of CT performance. This guide includes an extensive glossary (with discussion) of CT terminology and an extensive list of references to more technical publications on the subject. Most importantly, this guide establishes consensus definitions for basic measures of CT performance, enabling purchasers and suppliers of CT systems and services to communicate unambiguously with reference to a recognized standard. This guide also provides a few carefully selected equations relating measures of CT performance to key system parameters.

5.2 *General Description of Computed Tomography*—CT is a radiographic inspection method that uses a computer to reconstruct an image of a cross-sectional plane (slice) through an object. The resulting cross-sectional image is a quantitative map of the linear X-ray attenuation coefficient, μ, at each point in the plane. The linear attenuation coefficient characterizes the local instantaneous rate at which X-rays are removed during the scan, by scatter or absorption, from the incident radiation as it propagates through the object (See 7.5). The attenuation of the X rays as they interact with matter is a well-studied problem **(1)**[3] and is the result of several different interaction mechanisms. For industrial CT systems with peak X-ray energy below a few MeV, all but a few minor effects can be accounted for in terms of the sum of just two interactions: photoelectric absorption and Compton scattering **(1)**. The photoelectric interaction is strongly dependent on the atomic number and density of the absorbing medium; the Compton scattering is predominantly a function of the electron density of the material. Photoelectric attenuation dominates at lower energies and becomes more important with higher atomic number, while Compton scattering dominates at higher energies and becomes more important at lower atomic number. In special situations, these dependencies can be used to advantage (see 7.6.2 and references therein).

5.2.1 One particularly important property of the total linear attenuation coefficient is that it is proportional to material density, which is of course a fundamental physical property of all matter. The fact that CT images are proportional to density is perhaps the principal virtue of the technology and the reason that image data are often thought of as representing the distribution of material density within the object being inspected. This is a dangerous oversimplification, however. The linear attenuation coefficient also carries an energy dependence that is a function of material composition. This feature of the attenuation coefficient may or may not (depending on the materials and the energies of the X rays involved) be more important than the basic density dependence. In some instances, this effect can be detrimental, masking the density differences in a CT image; in other instances, it can be used to advantage, enhancing the contrast between different materials of similar density.

5.2.2 The fundamental difference between CT and conventional radiography is shown in Fig. 1. In conventional radiography, information on the slice plane "P" projects into a single line, "A-A;" whereas with the associated CT image, the full spatial information is preserved. CT information is derived from a large number of systematic observations at different viewing angles, and an image is then reconstructed with the aid of a computer. The image is generated in a series of discrete picture elements or pixels. A typical CT image might consist of a 512 by 512 or 1024 by 1024 array of attenuation values for a single cross-sectional slice through a test specimen. This resultant two-dimensional map of the slice plane is an image of the test article. Thus, by using CT, one can, in effect, slice open the test article, examine its internal features, record the different attenuations, perform dimensional inspections, and

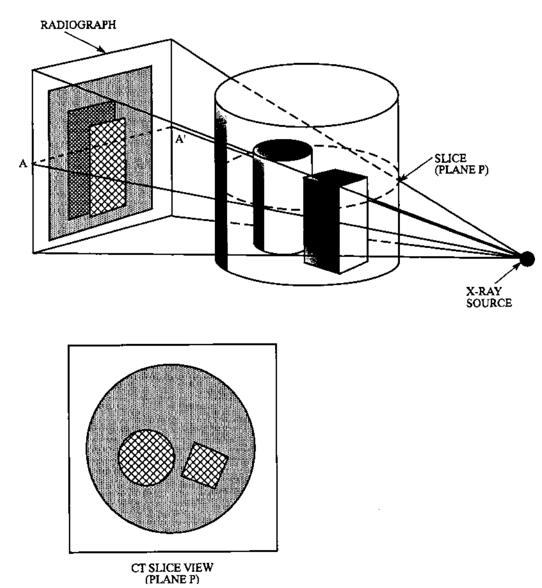

FIG. 1 A CT Image Versus a Conventional Radiograph

[3] The boldface numbers in parentheses refer to the list of references at the end of this standard.

identify any material or structural anomalies that may exist. Further, by stacking and comparing adjacent CT slices of a test article, a threedimensional image of the interior can be constructed.

5.2.3 From Fig. 1, it can be appreciated readily that if an internal feature is detected in conventional projection radiography, its position along the line-of-sight between the source and the film is unknown. Somewhat better positional information can be determined by making additional radiographs from several viewing angles and triangulating. This triangulation is a rudimentary, manual form of tomographic reconstruction. In essence, a CT image is the result of triangulating every point in the plane from many different directions.

5.2.4 Because of the volume of data that must be collected and processed with CT, scans are usually made one slice at a time. A set of X-ray attenuation measurements is made along a set of paths projected at different locations around the periphery of the test article. The first part of Fig. 2 illustrates a set of measurements made on a test object containing two attenuating disks of different diameters. The X-ray attenuation measurement made at a particular angle, ϕ_1, is referred to as a single view. It is shown as $f_{\phi 1}(x')$, where x' denotes the linear position of the measurement. The second part of Fig. 2 shows measurements taken at several other angles $f_{\phi i}(x')$. Each of the attenuation measurements within these views is digitized and stored in a computer, where it is subsequently conditioned (for example, normalized and corrected) and filtered (convolved), as discussed in more detail in Section 7. The next step in image processing is to backproject the views, which is also shown in the second part of Fig. 2. Backprojection consists of projecting each view back along a line corresponding to the direction in which the projection data were collected. The backprojections, when enough views are employed, form a faithful reconstruction of the object. Even in this simple example, with only four projections, the concentration of backprojected rays already begins to show the relative size and position of features in the original object.

5.3 *System Capabilities*—The ability of a CT system to image thin cross-sectional areas of interest through an object makes it a powerful complement to conventional radiographic inspections. Like any imaging system, a CT system can never duplicate exactly the object that is scanned. The extent to which a CT image does reproduce the object is dictated largely by the competing influences of the spatial resolution, the statistical noise, and the artifacts of the imaging system. Each of these aspects is discussed briefly here. A more complete discussion will be found in Sections 8 and 9.

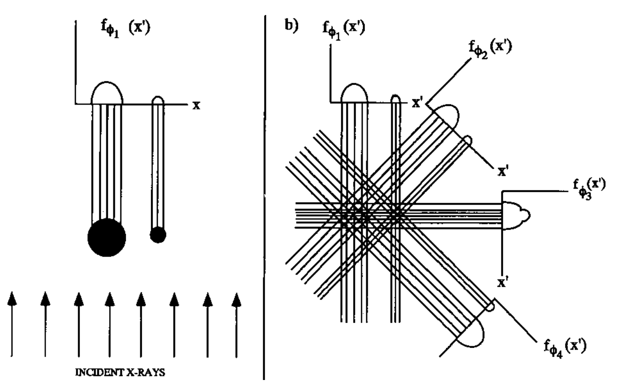

FIG. 2 Schematic Illustrations of How CT Works

5.3.1 *Spatial Resolution*—Radiographic imaging is possible because different materials have different X-ray attenuation coefficients. In CT, these X-ray coefficients are represented on a display monitor as shades of gray, similar to a photographic image, or in false color. The faithfulness of a CT image depends on a number of system-level performance factors, with one of the most important being spatial resolution. Spatial resolution refers to the ability of a CT system to resolve small details or locate small features with respect to some reference point.

5.3.1.1 Spatial resolution is generally quantified in terms of the smallest separation at which two points can be distinguished as separate entities. The limiting value of the spatial resolution is determined by the design and construction of the system and by the amount of data and sampling scheme used to interrogate the object of interest. The precision of the mechanical system determines how accurately the views can be backprojected, and the X-ray optics determine the fineness of the detail that can be resolved. The number of views and the number of single absorption measurements per view determine the size of the reconstruction matrix that can be faithfully reconstructed. Reducing pixel size can improve spatial resolution in an image until the inherent limit set by these constraints is reached. Beyond this limit, smaller pixels do not increase the spatial resolution and can induce artifacts in the image. However, under certain circumstances, reconstructing with pixels smaller than would otherwise be warranted can be a useful technique. For instance, when performing dimensional inspections, working from an image with pixels as small as one-fourth the sample spacing can provide measurable benefit.

5.3.1.2 It can also be shown that a given CT image is equivalent to the blurring (convolution) of the ideal representation of the object with a smooth, two-dimensional Gaussian-like function called the point-spread-function (PSF). The specification of the PSF of a system is an important characterization of a CT system and can be derived fairly accurately from the parameters of the CT system. The effect of the PSF is to blur the features in the CT image. This has two effects: (*1*) small objects appear larger and (*2*) sharp boundaries appear diffuse. Blurring the image of small objects reduces resolution since the images of two small point-like objects that are close together will overlap and may be indistinguishable from a single feature. Blurring sharp edges reduces the perceptibility of boundaries of different materials for the same reason. This effect is especially important at interfaces between materials, where the possibility of separations of one type or another are of the greatest concern. Thus, knowledge of the PSF of a CT system is crucial to the quantitative specification of the maximum resolution and contrast achievable with that system.

5.3.1.3 It should be noted, since it is a common source of misunderstanding, that the smallest feature that can be detected in a CT image is not the same as the smallest that can be resolved. A feature considerably smaller than a single pixel can affect the pixel to which it corresponds to such an extent that it will appear with a visible contrast relative to adjacent pixels.

This phenomenon, the "partial-volume effect," is discussed in 7.6. The difference between the resolution of a small feature and the resolution of its substructure is of fundamental importance for CT.

5.3.2 *Statistical Noise*—All images made from physical interactions of some kind will exhibit intrinsic statistical noise. In radiography, this noise arises from two sources: (*1*) intrinsic statistical variations due to the finite number of photons measured; and (*2*) the particular form of instrumentation and processing used. A good example in conventional radiography is film that has been underexposed. Even on a very uniform region of exposure, close examination of the film will reveal that only a small number of grains per unit area have been exposed. An example of instrumentationinduced noise is the selection of coarse- or fine-grain film. If the films are exposed to produce an image with a given density, the fine-grain film will have lower statistical noise than the coarse-grain film. In CT, statistical noise in the image appears as a random variation superimposed on the CT level of the object. If a feature is small, it may be difficult to determine its median gray level and distinguish it from surrounding material. Thus, statistical noise limits contrast discrimination in a CT image.

5.3.2.1 Although statistical noise is unavoidable, its magnitude with respect to the desired signal can be reduced to some extent by attempting to increase the desired signal. This can be accomplished by increasing the scan time, the output of the X-ray source, or the size of the X-ray source and detectors. Increasing the detector and source size, however, will generally reduce spatial resolution. This tradeoff between spatial resolution and statistical noise is a fundamental characteristic of CT.

5.3.3 *Artifacts*—An artifact is something in an image that does not correspond to a physical feature in the test object. All imaging systems, whether CT or conventional radiography, exhibit artifacts. Examples of artifacts common to conventional radiography are blotches of underdevelopment on a film or scattering produced by high-density objects in the X-ray field. In both cases, familiarity with these artifacts allows the experienced radiographer to discount their presence qualitatively.

5.3.3.1 CT artifacts manifest themselves in somewhat different ways, since the CT image is calculated from a series of measurements. A common artifact is caused by beam hardening and manifests itself as cupping, that is, a false radial gradient in the density that causes abnormally low values at the interior center of a uniform object and high values at the periphery. Artifacts occurring at the interfaces between different density materials are more subtle. There is often an overshoot or undershoot in the density profile at such a density boundary. The interface density profile must be well characterized so that delaminations or separations are not obscured. If the interface profile is not well characterized, false positive indications of defects or, more importantly, situations in which defects go undetected will result. Thus it is important to understand the class of artifacts pertinent to the inspection and to put quantitative limits on particular types of artifacts. Some of the artifacts are inherent in the physics and the mathematics of CT and cannot be eliminated (see 7.6). Others are due to hardware or software deficiencies in the design and can be eliminated by improved engineering.

5.3.3.2 The type and severity of artifacts are two of the factors that distinguish one CT system from another with otherwise identical specifications. The user must understand the differences in these artifacts and how they will affect the determination of the variables to be measured. For instance, absolute density measurements will be affected severely by uncompensated cupping, but radial cracks can be visible with no change in detectability.

6. Apparatus

6.1 Modern CT systems, both industrial and medical, are composed of a number of subsystems, typically those shown in Fig. 3. The choice of components for these subsystems depends on the specific application for which the system was designed; however, the function served by each subsystem is common in almost all CT scanners. These subsystems are:

6.1.1 An operator interface,
6.1.2 A source of penetrating radiation,
6.1.3 A radiation detector or an array of detectors,
6.1.4 A mechanical scanning assembly,
6.1.5 A computer system,
6.1.6 A graphical display system, and
6.1.7 A data storage medium.

6.2 *Operator Interface*—The operator interface defines what control the operator has over the system. From the perspective of the user, the operator interface is the single most important subsystem. The operator interface ultimately determines everything from the ease of use to whether the system can perform repetitive scan sequences. In short, the operator interface determines how the system is used.

6.3 *Radiation Sources*—There are three rather broad types of radiation sources used in industrial CT scanners: (*1*) X-ray tubes, (*2*) linear accelerators, and (*3*) isotopes. The first two broad energy spectra are (polychromatic or bremsstrahlung) electrical sources; the third is approximately monoenergetic radioactive sources. The choice of radiation source is dictated by precisely the same rules that govern the choice of radiation source for conventional radiographic imaging applications. A majority of existing CT scanners use electrical bremsstrahlung X-ray sources: X-ray tubes or linear accelerators. One of the primary advantages of using an electrical X-ray source over a radioisotope source is the much higher photon flux possible

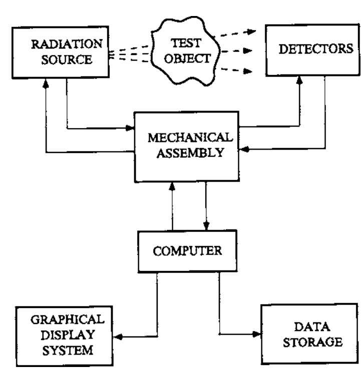

FIG. 3 Typical Components of a Computed Tomography (CT) System

with electrical radiation generators, which in turn allows shorter scan times. The greatest disadvantage of using an X-ray source is the beamhardening effect associated with polychromatic fluxes. Beam hardening results from the object preferentially absorbing low-energy photons contained in the continuous X-ray spectrum. Most medical scanners use for a source an X-ray tube operating with a potential of 120 to 140 kV. Industrial scanners designed for moderate penetrating ability also use X-ray tubes, but they usually operate at higher potentials, typically 200 to 400 kV. Systems designed to scan very massive objects, such as large rocket motors, use high-energy bremsstrahlung radiation produced by linear accelerators. These sources have both high flux and good penetration, but they also have a broad continuous spectrum and the associated beam-hardening effect. Isotope sources are attractive for some applications. They offer an advantage over X-ray sources in that problems associated with beam hardening are nonexistent for the monoenergetic isotopes such as Cesium137 and Cobalt-60. They have the additional advantages, which are important in some applications, that they do not require bulky and energy-consuming power supplies, and they have an inherently more stable output intensity. The intensity of available isotopic sources, however, is limited by specific activity (photons/second/gram of material). The intensity affects signal-to-noise ratio, and, even more importantly, the specific activity determines source spot size and thus spatial resolution. Both of these factors tend to limit the industrial application of isotopic scanners. Nevertheless, they can be used in some applications in which scanning time or resolution is not critical.

6.4 *Radiation Detectors*—A radiation detector is used to measure the transmission of the X rays through the object along the different ray paths. The purpose of the detector is to convert the incident X-ray flux into an electrical signal, which can then be handled by conventional electronic processing techniques. The number of ray sums in a projection should be comparable to the number of elements on the side of the image matrix. Such considerations result in a tendency for modern scanners to use large detector arrays that often contain several hundred to over a thousand sensors. There are essentially two general types of detectors in widespread uses: (*1*) gas ionization detectors and (*2*) scintillation counters detectors.

6.4.1 *Ionization Detectors*—In this type of transducer, the incoming X rays ionize a Noble element that may be in either a gaseous or, if the pressure is great enough, liquid state. The ionized electrons are accelerated by an applied potential to an anode, where they produce a charge proportional to the incident signal. Ionization detectors used in CT systems are typically operated in a current integration rather than pulse counting mode. In some embodiments of the technology, charge amplification can also be engineered. Ionization detectors are rugged and amenable to different implementations. A single detector enclosure can be segmented to create linear arrays with many hundreds of discrete sensors. High conversion and collection efficiencies have been achieved with high-pressure Xenon, which has a density in excess of 1.5g/cm^3 and an atomic number higher than many scintillators. Such detectors have been used successfully with 2-MV X-ray sources and show promise of being useful at higher energies as well.

6.4.2 *Scintillation Detectors*—This type of transducer takes advantage of the fact that certain materials possess the useful property of emitting visible radiation when exposed to X rays. By selecting fluorescent materials that scintillate in proportion to the incident flux and coupling them to some type of device that converts optical input to an electrical signal, sensors suitable for CT can be engineered. The light-to-electrical converter is usually a photodiode or photomultiplier tube, but video-based approaches are also widely employed. Like ionization detectors, scintillation detectors afford considerable design flexibility and are quite robust. Scintillation detectors are often used when very high stopping power, very fast pulse counting, or areal sensors are needed. Recently, for high-resolution CT applications, scintillation detectors with discrete sensors have been reported with array spacings on the order of 25 µm. Both ionization and scintillation detectors require considerable technical expertise to achieve performance levels acceptable for CT.

6.5 *Mechanical Scanning Equipment*— The mechanical equipment provides the relative motion between the test article, the source, and the detectors. It makes no difference, at least in principle, whether the test object is moved systematically relative to the source and detectors, or if the source and detectors are moved relative to the test object. Physical considerations such as the weight or size of the test article should be the determining factors for the most appropriate motion to use.

6.5.1 The majority of scan geometries that have been employed can be classified as one of the following four generations. This classification is a legacy of the early, rapid development of CT in the medical arena and is reviewed here because these terms are still widely used. The distinctions between the various scan geometries is illustrated in Fig. 4.

6.5.1.1 First-generation CT systems are characterized by a single X-ray source and single detector that undergo both linear

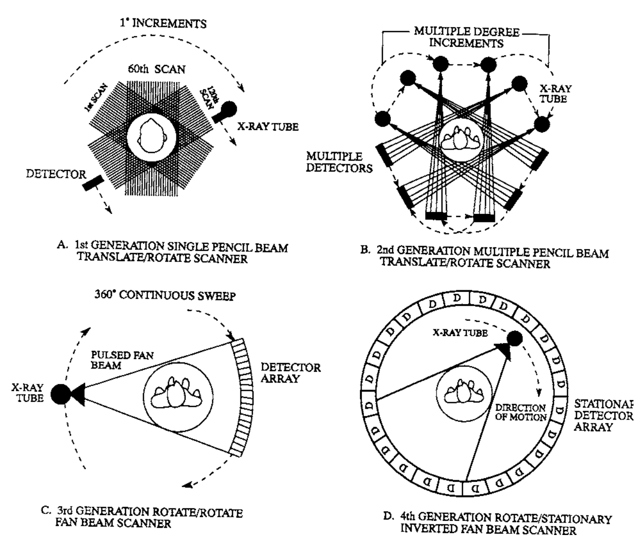

FIG. 4 Four Sketches Illustrating the Evolution of Medical CT Scan Geometries. Each Embodiment is Representative of a Distinct Generation of Instrumentation

translation and rotational motions. The source and detector assembly is translated in a direction perpendicular to the X-ray beam. Each translation yields a single view, as shown in Fig. 2. Successive views are obtained by rotating the test article and translating again. The advantages of this design are simplicity, good view-to-view detector matching, flexibility in the choice of scan parameters (such as resolution and contrast), and ability to accommodate a wide range of different object sizes. The disadvantage is a longer scanning time.

6.5.1.2 Second-generation CT systems use the same translate/rotate scan geometry as the first generation. The primary difference is that second-generation systems use a fan beam of radiation and multiple detectors so that a series of views can be acquired during each translation, which leads to correspondingly shorter scan times. Like first-generation systems, second-generation scanners have the inherent flexibility to accommodate a wide range of different object sizes, which is an important consideration for some industrial CT applications.

6.5.1.3 Third-generation CT systems normally use a rotate-only scan geometry, with a complete view being collected by the detector array during each sampling interval. To accommodate objects larger than the field of view subtended by the X-ray fan, it is possible to include part translations in the scan sequence, but data are not acquired during these translations as during first- or second-generation scans. Typically, third-generation systems are faster than their second-generation counterparts; however, because the spatial resolution in a third-generation system depends on the size and number of sensors in the detector array, this improvement in speed is achieved at the expense of having to implement more sensors than with earlier generations. Since all elements of a third-generation detector array contribute to each view, rotate-only scanners impose much more stringent requirements on detector performance than do secondgeneration units, where each view is generated by a single detector.

6.5.1.4 Fourth-generation CT systems also employ a rotate-only scan motion. The difference between third-generation and fourth-generation systems is that a fourth-generation CT system uses a stationary circular array of detectors and only the source moves. The test specimen is placed within the circle of detectors and is irradiated with a wide fan beam which rotates around the test article. A view is made by obtaining successive absorption measurements of a single detector at successive positions of the X-ray source. The number of views is equal to the number of detectors. These scanners combine the artifact resistance of second-generation systems with the speed of third-generation units, but they can be more complex and costly than first-, second-, or thirdgeneration machines, they require that the object fit within the fan of X-rays, and they are more susceptible to scattered radiation.

6.5.2 A significant factor in driving medical CT systems to use rotate-only scan geometries was the requirement that scanning times be short compared to the length of time that a patient can remain motionless or that involuntary internal motion can be ignored (that is, seconds). These considerations are not as important for industrial applications in which scan times for specific production-related items can typically be much longer (that is, minutes) and the dose to the object is often not an important factor. A secondgeneration scan geometry is attractive for industrial applications in which a wide range of part sizes must be accommodated, since the object does not have to fit within the fan of radiation as it generally does with third- or fourth-generation systems. A third-generation scan geometry is attractive for industrial applications in which the part to be examined is well defined and scan speed is important. To date, first- and fourth-generation scan geometries have seen little commercial application, but there may be special situations for which they would be well suited.

6.6 *Computer Systems*—The computer system(s) performs two major tasks: (*1*) controlling the scan motion, source operation, and data acquisition functions; and (*2*) handling the reconstruction, image display and analysis, and data archival and retrieval functions. Most modern CT systems partition these functions between separate dedicated microprocessors. Image formulation operations involve intensive computation, and they are almost always performed with array processors and specially designed hardware.

6.7 *Image Display and Processings*— Image display and processing are subfunctions of the computer system that provide a degree of image interaction not available with conventional radiography. The mapping between the pixel linear attenuation coefficient and the displayed intensity of the pixel can be changed to accommodate the best viewing conditions for a particular feature. Image processing functions such as statistical and densitometric analyses can be performed on an image or group of images. The digital nature of the image allows major advances in the way data are processed and analyzed and stored. This process of mapping reconstructed pixel values to displayed pixel values is shown in Fig. 5.

6.8 *Archival Data Storage*—Information such as image data, operating parameters, part identification, operator comments, slice orientation, and other data is usually saved (archived) in a computer-readable, digital format on some type of storage medium (for example, magnetic tape, floppy disk, or optical disk). The advantage of saving this material in computer-readable format rather than in simple hardcopy form is that it would take dozens of pictures of each slice at different

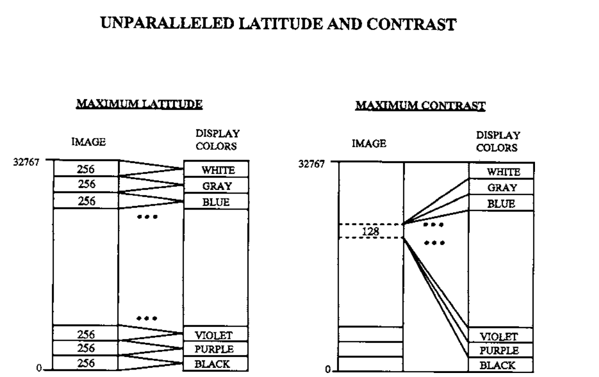

FIG. 5 Conceptual Illustration of the Process of Mapping a Large Range of Image Values Onto a Much Smaller Range of Displayable Values. Two Important Cases are Shown: the One on the Left Illustrates the Case of Maximum Image Latitude; the One on the Right Illustrates the Case of Maximum Contrast Over a Narrow Range of Contrast

display conditions to approximate the information contained in a single CT image. Also, images of samples made with old and new data sets can be compared directly, and subsequent changes in reconstruction or analysis procedures can be reapplied to saved data or images.

6.9 These elements are the basic building blocks of any CT system. Each CT system will have its own particular set of features. It is the responsibility of the user to understand these differences and to select the system most appropriate for the intended application.

7. Theoretical Background

7.1 *Background* —This section will cover the theoretical background associated with CT. First, the means of penetrating radiation interaction will be discussed. Second, the specifics of CT will be delineated.

7.2 *X-Ray Interactions*—Penetrating radiation is classified according to its mode of origin. Gamma rays are produced by nuclear transitions and emanate from the atomic nucleus. Characteristic X rays are produced by atomic transitions of bound electrons and emanate from the electronic cloud. Continuous X rays, or bremsstrahlung, are produced by the acceleration or deceleration of charged particles, such as free electrons or ions. Annihilation radiation is produced by the combination of electron-positron pairs and their subsequent decomposition into pairs of photons. All evidence suggests that the interaction of these photons with matter is independent of their means of production and is dependent only on their energy. For this reason, this document refers to penetrating radiation in the energy range from a few keV to many MeV as X rays, regardless of how they are produced.

7.2.1 X rays can in theory interact with matter in only four ways: they can interact with atomic electrons; they can interact with nucleons (bound nuclear particles); they can interact with electric fields associated with atomic electrons and/or atomic nuclei; or they can interact with meson fields surrounding nuclei. In theory, an interaction can result in only one of three possible outcomes: the incident X-ray can be completely absorbed and cease to exist; the incident X-ray can scatter elastically; or the incident X-ray can scatter inelastically. Thus, in principle, there are twelve distinct ways in which photons can interact with matter (see Fig. 6). In practice, all but a number of minor phenomena can be explained in terms of just a few principal interactions; these are highlighted in Fig. 6. Some of the possible interactions have yet to be physically observed.

7.2.2 The photon-matter interactions of primary importance to radiography are the ones which dominate observable phenomenon: photoelectric effect, Compton scattering, and pair production. Their domains of relative importance as a function of photon energy and material atomic number are shown in Fig. 7. At energies below about 1 MeV, pair production is not allowed energetically; and X-ray interactions with matter are dominated by processes involving the atomic electrons. Of the other possible interactions (see Fig. 6), Rayleigh scattering is typically small but non-negligible; the rest are either energetically forbidden or insignificant. At energies above 1 MeV, pair production is energetically allowed and competes with Compton scattering. Of the other possible interactions, photodisintegration is typically negligible in terms of measurable attenuation effects, but at energies above about 8 MeV can lead to the production of copious amounts of neutrons. The rest of the interactions are either energetically forbidden or insignificant.

7.2.3 The three principle interactions are schematically illustrated in Fig. 8. With the photoelectric effect (see Fig. 8), an incident X ray interacts with the entire atom as an entity and is completely absorbed. To conserve energy and momentum, the atom recoils and a bound electron is ejected. Although the subsequent decay processes lead to the generation of characteristic X rays and secondary electrons, these are not considered part of the photoelectric effect. As can be seen in Fig. 7, the photoelectric effect predominates at low energies. Photoelectric absorption depends strongly upon atomic number, varying approximately as z raised to the 4th or 5th power.

7.2.4 With Compton scattering (see Fig. 8), an incident X-ray interacts with a single electron (which, practically speaking, is almost always bound) and scatters inelastically, meaning the X-ray loses energy in the process. This type of scattering is often referred to as incoherent scattering, and the terms are used interchangeably. To conserve energy and momentum, the electron recoils and the X-ray is scattered in a different direction at a lower energy. Although the X-ray is not absorbed, it is removed from the incident beam by virtue of having been diverted from its initial direction. The vast majority of beakground radiation in and around radiographic equipment is from Compton-scattered X rays. As can be seen

Effects of Interaction	Atomic Electrons	Nucleons	Electric Field Of Atom	Meson Field Of Nucleus
Complete Absorption	Photoelectic Effect	Photo Disintegration	Pair Production	Meson Production
Elastic Scattering	Rayleigh Scattering	Thomson Scattering	Delbruck Scattering	Not Observed
Inelastic Scattering	Compton Scattering	Nuclear Resonance Scattering	Not Observed	Not Observed

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FIG. 6 X-Ray Interactions with Matter

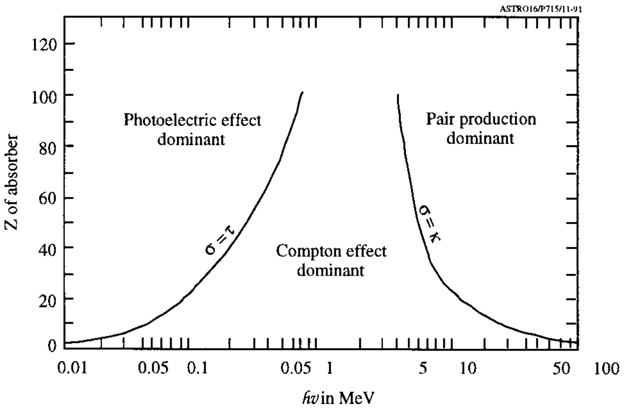

FIG. 7 Principal X-Ray Interactions

in Fig. 7, Compton scattering predominates at intermediate energies and varies directly with atomic number per unit mass.

7.2.5 With pair production (see Fig. 8), an incident X-ray interacts with the strong electric field surrounding the atomic nucleus and ceases to exist, creating in the process an electron-positron pair. Energy and momentum are conserved by the emerging pair of particles. Although the positrons eventually interact with electrons, generating annihilation radiation, this secondary effect is not considered part of the pair production process. As can be seen in Fig. 7, pair production predominates at high energies. Pair production varies approximately with atomic number as $z\ (z + 1)$.

7.3 *CT Technical Background*—CT is the science of recovering an estimate of the internal structure of an object from a systematic, nondestructive interrogation of some aspect of its physical properties. Generally, but not always **(2)**, the problem is kept manageable by limiting the task to a determination of a single image plane through the object. If three-dimensional information is required, it is obtained by comparing and, if necessary, resectioning **(3)** contiguous cross-sections through the object of interest.

7.3.1 In its most basic form, the CT inspection task consists of measuring a complete set of line integrals involving the physical parameter of interest over the designated cross-section and then using some type of computational prescription, or algorithm, to recover an estimate of the spatial variation of the parameter over the desired slice. In order to best illustrate the basic principles of CT, the discussion limits itself to the examination problem of determining a single image plane through an object. Separate sections focus on (*1*) what constitutes an acceptable CT data set, (*2*) one way in which such a data set can be collected, and (*3*) some of the competing effects that limit performance in practice. The discussion of the companion task of image reconstruction limits itself to the problem of reconstructing a single two-dimensional image; three-dimensional reconstructions are not discussed. The treatment includes the goal of the reconstruction process and one way in which CT data can be reconstructed.

7.3.2 The task of obtaining a useable data set is reviewed in 7.4-7.6. The companion problem of how these data are then reconstructed to produce an image of the object is reviewed in 7.7 and 7.8.

7.4 *Radon Transform*—The theoretical mathematical foundation underlying CT was established in 1917 by J. Radon **(4)**. Motivated by certain problems of gravitational physics, Radon established that if the set of line integrals of a function, which is finite over some region of interest and zero outside it, is known for all ray paths through the region, then the value of the function over that region can be uniquely determined. A particular function and its associated set of line integrals form a transform pair; the set of integrals is referred to as the Radon transform of the function. Radon demonstrated the existence of an inverse transform for recovering a function from its Radon transform, providing an important existence theorem for what later came to be called CT. Over the years, the process of recovering a function from its Radon transform has been rediscovered numerous times **(5-9)**.

7.4.1 In a classic example of the old principle that" like equations have like solutions," tomography has been demonstrated using many different physical modalities to obtain the necessary line integrals of some physical parameter. Objects ranging in size from bacteriophages **(10)** to supernova **(11)** have been studied tomographically using a wide variety of physical probes, including X rays (medical CAT scanners or simple X-ray CT) **(12, 13)**, sound waves (ultrasonic imaging) **(14, 15)**, electromagnetic fields (NMR, or, more commonly now, MR imaging) **(16)**, ionizing particles **(17, 18)**, and biologically active isotopes (SPECT and PET scanners) **(19-21)**. These methods have been used to study many types of material properties, such as X-ray attenuation, density, atomic number, isotopic abundance, resistivity, emissivity, and, in the case of living specimens, biological activity.

7.4.2 The essential technological requirement, and that which these various methods have in common, is that a set of systematically sampled line integrals of the parameter of interest be measured over the cross-section of the object under inspection and that the geometrical relationship of these measurements to one another be well known. Within this constraint, many different methods of collecting useful data exist, even for the same imaging modality. However, the quality of the resulting reconstruction depends on at least three major factors: (*1*) how finely the object is sampled, (*2*) how accurately the individual measurements are made, and (*3*) how precisely each measurement can be related to an absolute frame of reference.

7.5 *Sampling the Radon Transform*—Given this general background, the discussion here now focuses on the specific task of tomographic imaging using X rays as the inspection modality. For monoenergetic X rays, attenuation in matter is governed by Lambert's law of absorption **(22)**, which holds that each layer of equal thickness absorbs an equal fraction of the radiation that traverses it. Mathematically, this can be expressed as the following:

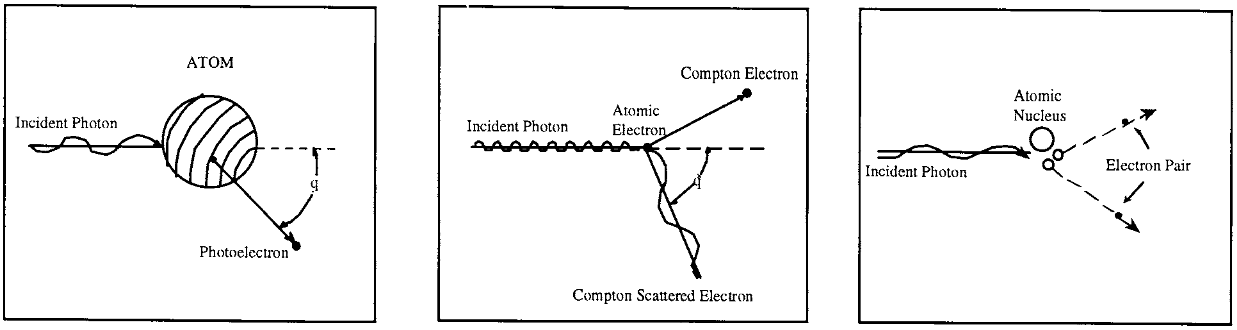

FIG. 8 X-Ray Interaction Mechanisms

$$\frac{dI}{I} = -\mu dx \qquad (1)$$

where:

I = the intensity of the incident radiation,
dI/I = the fraction of radiation removed from the flux as it traverses a small thickness, dx, of material, and
μ = the constant of proportionality.

In the physics of X-ray attenuation, μ is referred to as the linear absorption coefficient. Eq 1 can be integrated easily to describe X-ray attenuation in the following perhaps more familiar form **(1)**:

$$I = I_o e^{-\mu x} \qquad (2)$$

where:

I_o = the intensity of the unattenuated radiation, and
I = the intensity of the transmitted flux after it has traversed a layer of material of thickness x.

7.5.1 If X rays penetrate a non-homogeneous material, Eq 2 must be rewritten in the more general form:

$$I = I_o e^{-\int \mu(s) ds} \qquad (3)$$

where the line integral is taken along the direction of propagation and $\mu(s)$ is the linear absorption coefficient at each point on the ray path. In X-ray CT, the fractional transmitted intensity, I/I_o, is measured for a very large number of ray paths through the object being inspected and is then logged to obtain a set of line integrals for input to the reconstruction algorithms. Specifically, the primary measurements, I and I_o, are processed, often "on the fly," to obtain the necessary line integrals:

$$\int \mu(s) ds = -ln(I/I_o) \qquad (4)$$

7.5.2 To obtain an adequate measure of the line integrals, highly collimated pencil beams of X rays are used to make the measurements of the fractional transmittance. In the terminology of CT, the set of line integrals resulting from a scan of an object can be grouped conceptually into subsets referred to as views. Each view corresponds to a set of ray paths through the object from a particular direction (see Fig. 9). The views are also referred to as projections or profiles, while each individual datum within a given projection is referred to as a sample or often simply a data point.

7.5.3 As previously indicated, the reconstruction problem places a number of severe constraints on the data. First, the set of line integrals must represent a systematic sampling of the entire object. If the circle of reconstruction is inscribed in an M by M image matrix, this implies $(\pi/4)\ M^2$ unknowns and a need

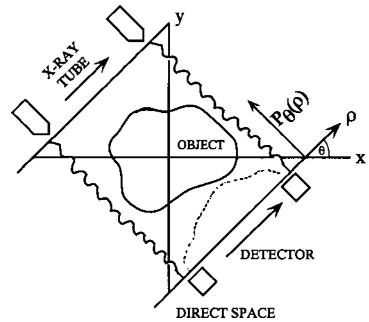

FIG. 9 Schematic Illustration of Basic CT Scan Geometry Showing a Single Profile Consisting of Many Discrete Samples

for at least $(\pi/4)\ M^2$ linearly independent measurements. Refs **(23-25)** have examined the minimum number of views and samples per view necessary to reconstruct an arbitrary object from data in which the dominant source of noise is photon statistics. Since the presence of random noise corrupts the data, one would expect the minimum sampling requirements to be greater than they are for noise-free data as well as to be sensitive to the algorithm employed. Surprisingly, most algorithms in use today can provide stable, high-quality reconstructions for data sets approaching the theoretical minimum sampling requirements. Typically, data set sizes are on the order of one to three times the minimal amount, depending on the system and the application. Arbitrarily complex objects require more data than objects with simple geometrical shapes or highly developed symmetries.

7.5.4 The number of views and samples needed depends on the approach used and the amount of data required; however, independent of approach, the number of samples per view is generally more important than the number of views, and the relative proportion of views and samples should reflect this principle. Predicting the amount of noise in a CT image reconstructed with an adequate number of samples and views is a well-studied problem **(23-26)**; predicting the amount of noise when an insufficient number of samples or views, or both, is used is more difficult and less well studied **(24, 27)**.

7.5.5 Second, each line integral must be accurately known. It has been found that errors in the measurement of the fractional transmittance of even a few tenths of one percent are significant **(28)**. This places strict requirements on the data acquisition system. As a result, the radiation detectors used in standard X-ray CT systems, along with their associated electronics, represent some of the most sophisticated X-ray sensor technology developed to date. A typical CT system can handle a dynamic range (the ratio of peak signal-strength-to-rms noise) on the order of a millionto-one **(29, 30)**, with a linearity of better than 0.5 % **(30, 31)**.

7.5.6 Third, each sample must be referenced accurately to a known coordinate system. It is useless to have highprecision transmission measurements if the exact ray path through the object to which it corresponds is unknown. This places strict demands on the mechanical equipment. Studies have shown that the angle of each view must be known to within a few hundredths of a degree, and the linear position of each sample within a given projection must be known to within a few tens of micrometres **(28)**.

7.5.7 CT equipment has evolved to the stage at which each of these performance requirements can be reasonably well satisfied. A state-of-the-art scanner routinely collects millions of measurements per scan, with each one quantified accurately and referenced precisely to a specific line-of-sight through the object of interest. Once collected, the data are then passed to the reconstruction algorithm for processing.

7.6 *Physical Limitations on the Sampling Process*—The quality of the reconstructed image depends on the quality of the data generated by the scanner. In actual practice, equipment and methods are limited in their ability to accurately estimate line integrals of the attenuation through an object **(32)**. Some of the more prominent sources of inaccuracy are the following: photon statistics, beam hardening, finite width of the X-ray pencil beams, scattered radiation, and electronic and hardware nonlinearities or instabilities, or both. Considerable attention is devoted to managing these problems.

7.6.1 The penetrating radiation used by CT systems is produced in a number of ways, all of which involve random atomic or subatomic processes, or both. The probability of any one atom participating at any given moment in time is remote, but the sheer numbers of atoms typically involved guarantees a finite emission rate. The number of photons produced per unit time varies because of the statistical nature of the radiation emission process. The variations have well-defined characteristics, which can be described by what are referred to mathematically as Poisson statistics. This ubiquitous radiographic problem of photon statistics is handled in CT by integrating (or counting) long enough to keep statistical noise to a diagnostically acceptable level **(27, 33)**. What constitutes an acceptable noise level is defined by the application and can vary widely.

7.6.2 Beam hardening is a problem encountered with polychromatic X-ray sources, such as X-ray tubes or linear accelerators (linacs). Such bremsstrahlung sources, as opposed to monoenergetic (that is, isotopic) sources, produce a flux whose average radiation energy becomes progressively higher as it propagates through an object because the lower-energy photons are preferentially absorbed with respect to the more energetic ones. This effect compromises the validity of Eq 4 since μ is no longer associated with a single energy but rather with an effective energy that is constantly changing along the ray path. Although this effect can be partially controlled by conscious engineering choices, it is generally a significant problem and must be corrected for at some stage in the reconstructive processing (see Refs **(34-36)** and references therein).

7.6.3 Another source of difficulties is with the finite width of the individual pencil beams. A pencil beam of X rays is geometrically defined by the size of the focal spot of the X-ray source and the active area of each detector element. Because these are finite, each source-detector line-of-sight defines a thin strip rather than an infinitely thin mathematical line. As a result, each measurement represents a convolution of the desired line integral with the profile of the pencil beam. In general, the width of the strip integrals is small enough that although some loss of spatial information occurs, no distracting artifacts are generated. The exception occurs when there are sharp changes in signal level. The error then becomes significant enough to produce artifacts in the reconstructed image which manifest themselves in the form of streaks between high-contrast edges in the image. These edge artifacts **(32, 37-39)** are caused by the mathematical fact that the logarithm of the line integral convolved with the profile of the pencil beam (which is what is measured) does not equal the convolution of the beam profile with the logarithm of the line integral (which is what the reconstruction process desires).

7.6.4 Unfortunately, edge artifacts cannot be eliminated by simply reducing the effective size of the focal spot or the detector apertures, or both, through judicious collimation. As the strip integrals are reduced to better approximate line integrals and reduce susceptibility to edge artifacts, count rates become severely curtailed, which leads to either much noisier images or much longer scan times, or both. In practice, the pencil beams are engineered to be as small as practicable, and if further reductions in edge-artifact content are required, these are handled in software. However, software corrections entail some type of deconvolution procedure to correct for the beam profile **(32, 37-39)** and are complicated by the fact that the intensity profile of the pencil beam has a complex geometrical shape that varies along the path of the X rays.

7.6.5 The same problem occurs when the structure of the object undergoing inspection changes rapidly in the direction normal to the plane of the scan. When the change is sizeable over the thickness of the slice, the same mathematics that lead to the edge artifact produce what in this case is commonly referred to as a partial-volume artifact **(32, 37-39)**. It manifests itself as an apparent reduction in attenuation coefficient in those parts of the image where the transverse structure is changing rapidly. In the absence of *a priori* information, nothing is known about the spatial variation of object structure within the plane of the scan, and software corrections are much more difficult to implement.

7.6.6 Still another source of problems arises from the presence of scattered radiation. When multiple detector elements are employed, there is always the chance that radiation removed from the incident flux by Compton interactions will be registered in another detector. This scattered radiation, which becomes more severe with higher energies, cannot be easily distinguished from the true signal and corrupts the measurements. This problem can be reduced **(40)**, but not eliminated, through the use of proper collimation.