White paper:

Patient Exposures in Computed Tomography Exams Deserve Our Attention

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Radiation dose from Computed Tomography (CT) exams has recently become a hot topic among the medical community, the legal community, and the public in general. Overdoses from brain perfusion studies at several medical facilities in California and Alabama have contributed to this rise in concern. Reports of these specific instances as well as general discussions of CT effects can be found in multiple news stories, including NPR reports, USA Today articles, and ABC News, among many others.

Doses imparted in CT exams exceed those from conventional radiography exams, sometimes by more than an order of magnitude. The use of CT has been growing extensively in the recent past, with an estimate of 62 million exams in 2006 alone. This combination of high individual exam dose and large numbers of total exams has caused CT to be the #1 medical imaging contributor to overall exposure to the US population.

Some of the important concerns and questions about CT and patient radiation dose include what information is provided to the CT technologist by the machine, how much a patient is receiving from a given scan, what information is provided to the patient by the technologist or the radiologist, and how can the dose be reduced as much as possible while still providing adequate medical care.

It is important to understand what information the system is capable of providing about the procedure as well as how the amount and quality of radiation produced by the scanner impacts the patient.

Radiation Dose

Radiation absorbed dose (D) is defined as the amount of energy absorbed (E) in a given amount of material (M), thus $D = E/M$. The material typically of concern in patient examinations is the patient's body itself, composed of various organs and tissues. If the same amount of energy is absorbed in a large patient and a small patient, the small patient is said to have a larger absorbed dose, because of the smaller amount of material present. Similarly, if a small patient is examined using less radiation than a large patient, the same absorbed dose can be achieved. The amount of dose received is related to the possibility of undesired effects, such as cancer induction.

CT Reported Information

Computed Tomography systems typically report two pieces of information related to radiation dose about each scan, the volume Computed Tomography Dose Index ($CTDI_{vol}$) and the Dose-Length Product

(DLP). In order to understand how these might relate to a patient's dose, we need to look into them in more detail.

$CTDI_{vol}$ represents the absorbed dose(in units of mGy) within the irradiated volume along an axis of a cylindrical phantom, corrected for the fact that the dose varies across the field of view (FOV) and also varies as a function of the coverage of the scan (overlapping slices, abutting slices, or gaps between slices). The phantom is defined in federal legislation as being made of polymethyl methacrylate with a specific density (1.19 ± 0.01 g/cm^3), which must be > 14 cm in length, and which must be 32 cm in diameter for testing whole body scan protocols or 16 cm in diameter for testing head scan protocols.

The key take-away from this formal definition is that the value of $CTDI_{vol}$ as defined does not relate to any absorbed dose in an actual human patient. The material specified is close in density to human tissues (fat ≈ 0.9 g/cm^3, muscle ≈ 1.06 g/cm^3, and bone ≈ 1.5 g/cm^3). However there are many additional complications which will be discussed in the next section.

The formal definition of $CTDI_{vol}$ only takes into account the radiation emitted over the length of a 100 mm scan. The actual dose averaged over the full volume of the scan will increase with scan length.

The DLP parameter attempts to take into account the different lengths along the patient that can be scanned with different protocols. It is defined as the average $CTDI_{vol}$ for the scan multiplied by the length of the scan in cm. Thus its units are mGy*cm. It reflects the total energy absorbed due to the complete scan acquisition. For example, if the same protocol settings are used for an abdomen only scan as for an abdomen/pelvis scan, the DLP will be greater for the abdomen/pelvis as more patient length is exposed.

Determining Possible Patient Harm from Radiation

To accurately determine a patient's true dose from a specific CT exam would involve measuring organ doses in patient-like phantoms. Since no two patients are exactly alike, this would be a prohibitive solution to implement for every individual undergoing a CT exam.

The size and shape of organs differ greatly from patient to patient and every patient consists of multiple organ and tissue types arranged in complicated relationships to one another. Since the x-ray tube in the CT system is rotating around the patient, organs can provide shielding to other organs from the radiation at one angle, and become the shielded organ once the x-ray tube has traveled 180° around the patient. In addition, scans of different patients might not result in the same amount of the same organs being irradiated. The amount of radiation absorbed and the effect of this absorbed dose will obviously depend on how much of each organ is exposed.

An alternative to actually scanning and measuring dose in physical phantoms is to perform calculations using Monte Carlo simulations of the large number of x-ray photons produced by the CT as they interact with computer models of the patient. Applying the results of these calculations to actual patients would require that the patient resembles the model. If differences in size and composition exist, correction strategies would have to be employed.

Software packages exist based on data pre-calculated by several different groups, such as the National Radiological Protection Board (NRPB) in the UK or the Institute of Radiation Protection (GSF) in Germany.

These two options would allow a determination of absorbed dose on an organ by organ basis for a model or standard patient, but would not tell us about the potential harm the exam could do. Tissues have different levels of radiosensitivity which would have to be taken into account. For example, the skin is much less radiosensitive than such organs as the colon, lung, stomach or breast tissue. Thus, a 10 mGy absorbed dose in an extremity would not have the same detriment as a 10 mGy absorbed dose in the pelvis. Patients can even vary in how sensitive their organs are to radiation, either because of genetic differences or pathology.

The varying radiosensitivity of tissues needs to be taken into account when determining any harm caused to the patient by the absorbed radiation. Effective dose (E) reflects this difference. It is calculated by multiplying each organ's absorbed dose by a tissue weighting factor, and then summing up for all exposed organs. The weighting factors take into account the varying radiosensitivity.

Effective dose is thus a single parameter that reflects the risk of a non-uniform (non-whole body) exposure to an equivalent whole-body exposure.

For the purposes of CT exams, the effective dose is calculated by multiplying the DLP parameter by a conversion factor that is dependent on the anatomy being exposed during the examination. These conversion factors are based on comparisons of different detailed calculation methods, and are based on large scale sections of the patient's anatomy. For example, there are factors for head scans, neck scans, thorax scans, abdomen scans, and pelvis scans.

As detailed as the calculations of E are for CT examinations, it is important to remember that effective dose was designed for radiation harm averaged over gender and age, and was not designed to be used for individual patients. The conversion factors are based on models of a "standard" human body that is most likely very different from the actual patient.

Dose Reduction Strategies

There are many strategies being employed by various CT manufacturers to reduce dose to patients while still maintaining adequate image quality for diagnostic purposes. Not all possibilities are available on every machine or from every manufacturer. We'll examine some of the concepts for dose reduction without getting into details of how a given system or manufacturer has implemented them.

Different protocols should be programmed and stored on the CT scanner based on a patient's size or weight. The simplest division of protocols would be adult versus pediatric. However, pediatric patients can vary from newborns through 18 years old, so finer divisions should be considered. At least one manufacturer provides a weight-based set of protocols with 9 separate sets of techniques covering the range from 13 lbs. to 121 lbs. If the binary child/adult separation is used with only two sets of a given anatomical protocol stored, then manual adjustment of the techniques should be implemented. Varied parameters should include the kVp and the mA and time or mAs combination.

The primary vendors of CT systems (GE, Siemens, Toshiba and Philips) all have systems available which will implement automatic exposure control (AEC), dynamically changing the mA or mAs of the x-ray tube as the examination progresses. The x-ray tube current can change either as a function of changes along the z-axis of the patient, or even as a function of changes in attenuation through the patient as the tube travels around the patient. The ultimate in mA/mAs modulation would be a combination of these variations.

Increasing or decreasing the x-ray tube current results in more or less radiation being produced and thus more or less dose being absorbed by the patient. The noise in the reconstructed images of a CT exam is dominated by the noisiest projection through the patient, which would correspond to the most attenuating projection through the patient. Thus thicker or more dense projections, such as laterally through the shoulder girdle or through the abdomen, will require more radiation to keep the image noise at acceptable levels.

The purpose of the exam can also impact how much noise is acceptable, and thus how much radiation should be used. High contrast exams such as those with large contrasts in attenuation properties (tissue vs. bone for skeletal exams, air vs. tissue for lung exams) can be adequately performed with noisier images, and thus lower doses to the patients. Low contrast exams such as brain, liver and soft tissue exams, will require lower noise values and thus higher doses. Noise levels or reference images with acceptable noise are used by the various AEC mechanisms in current CT systems.

The AEC systems function by taking CT radiographs (scout, scanogram, or topogram data) of the patient before the actual scan, in order to determine variations along the z-axis of the patient. Angular variations in tube current use live feedback from the detectors during the actual CT procedure to determine appropriate settings. Specialized software and hardware is involved in performing the rapid variations in tube output necessary for such dose reduction mechanisms.

At least one CT vendor is implementing an Automatic Tube Voltage Control system in which the CT projection radiograph is analyzed in conjunction with the diagnostic task specified in order to recommend which kVp value should be used to maintain acceptable noise levels.

The method of reconstructing the transverse images from the projection data will impact the amount of noise present. Advanced techniques such as iterative reconstruction are able to attain lower noise values with noisier input data, and thus can allow the actual exam to be conducted with less radiation. Note that this can only reduce the dose to the patient if it is known that the reconstruction method will be used. It wouldn't be possible to reduce the dose after the scan when it was realized that reconstruction should allow it.

All of these potential dose reduction strategies should be investigated by the imaging team at the CT facility, including the technologist, the radiologist, and the physicist. Implementing dose reduction can have significant results in lowering patient dose; however the entire team must be involved to ensure that quality of patient care is not sacrificed.

Patient Dose Tracking

Vendors of CT equipment and professional associations involved in medical imaging are all working towards a better method of tracking and documenting patient doses in addition to ensuring that examinations are conducted with the least amount of radiation possible.

Diagnostic reference levels are specific $CTDI_{vol}$ and/or DLP values for a given type of examination on a given type of patient, without regard for patient specific variations. For example, a reference level might be specified for an adult head exam, or a pediatric abdomen exam. These values are typically set by 3rd-party organizations based on large surveys of exams across multiple institutions. The most commonly encountered set of reference levels in the US is that of the American College of Radiology (ACR), in use with their CT Accreditation Program (CTAP). The $CTDI_{vol}$ values set by this organization are shown below:

Exam Type	**$CTDI_{vol}$ (mGy)**
Adult Head	75
Adult Abdomen	25
Pediatric Head	45
Pediatric Abdomen	20

If an institution's measured CTDIvol values exceed these reference levels, the ACR recommends that the protocol be investigated to determine if lower radiation levels can be utilized without loss of patient care.

Dose notification and dose alert levels are $CTDI_{vol}$ values set either for a specific protocol or for a series of protocols performed on a single patient that the system uses to alert the technologist if too much radiation is planned to be used. They are implemented by the CT equipment vendors to allow a facility to define warning levels and require interaction with the system by the technologist before the next scan can be performed. Some interfaces will allow the technologist to return to the protocol settings page, while others will require the user to input a specific medical reason for the examination to continue.

Radiation Dose Structured Reports (RDSRs) are collections of data involving the radiation characteristics of a patient's set of exams coded into the DICOM format of the examination data. The data is typically accessed using an RDSR viewer. Several 3rd-party vendors have offerings available.

Summary

With the increasing use of computed tomography exams in the medical imaging community, and the ability of individual CT exams to produce large amounts of radiation, it is imperative that the imaging teams work together to both reduce and document patient's exposure to radiation. The ability to generate amazingly detailed and clear images must be tempered with the knowledge that the cost of such imaging is potential harm to the patient.

While determining actual patient absorbed dose is a complicated process, CT systems today provide useful metrics such as $CTDI_{vol}$, DLP, Dose Notification Levels, and Dose Alert Levels, that allow every member of the team to work together for lower patient exposure.

New dose reductions strategies such as automated current modulation, automated tube voltage modification, and iterative reconstruction can be implemented to make lower patient exposures more automatic and robust. Managing and tracking patient exposures can likewise be easily implemented.

It is incumbent on all members of the CT imaging team, the technologist, the radiologist, and the physicist, to be involved with this process and work together to provide the best patient care possible with the least radiation possible.

References

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