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Understanding Computed Tomography (CT) Dose Reduction Techniques and Principles in a Simplified Way

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Abstract

Use of computed tomography (CT) has increased tremendously over the last two decades. Compared to the lowest dose x-ray techniques, CT scans can have 100 to 1,000 time's higher radiation dose than conventional X-rays. Despite its usefulness, potential risk of radiation induced malignancy does exist which cannot be ignored. One study estimated that as much as 0.4% of all current cancers in the United States are attributable to CT examinations based on CT usage data from 1991–1996. Hence it is imperative to know about CT dose reduction techniques. This review will give readers an insight to strategies for dose reduction and principles behind them.

Keywords: Dose Reduction; Radiation risk; Computed tomography; ALARA principle; Tube current (mA) modulation

Abbreviations: ALARA: As Low As Reasonably Achievable; DLP: Dose length product; $CTDI_{vol}$: Volume CT Dose Index; ICRP: The International Commission on Radiological Protection; DQE: Detective Quantum Efficiency; AEC: Automatic Exposure Control; HYPR-LR: Highly Constrained Back Projection Local Reconstruction; MBF: Multiband Filtering

Introduction

Since the risk of radiation induced malignancy attributable to CT is not totally zero and in light of dramatic increase in number of CT scans, dose reductions strategies are one of important consideration [1]. Since there is a definite benefit of CT scan in diagnosis and planning therapeutic procedures, a risk-benefit assessment should be done in each individual.

Guiding principles of radiation protection

There are three guiding principles for radiation protection in current clinical practice [2-4].

Justification: CT examination must be appropriately justified in each individual. Unless there is a sufficient benefit to offset the detrimental effect of radiation, CT scan should be avoided.

It is the shared responsibility of requesting clinicians and radiologists which helps in directing patients for the most appropriate imaging modality.

Optimization: Simply known as ALARA principle (As Low as Reasonably Achievable). It means for each diagnostic task, all technical aspects of examination must be optimized in relation to magnitude of doses, number of people exposed etc. such that necessary diagnostic information can be obtained while keeping dose as low as possible.

Limitation: To keep dose levels to occupationally expose individuals limited to levels recommended by consensus organisations. For example, Atomic Energy Regulatory Board (AERB) in India.

Before discussing further, it is important to know about quantifying CT radiation output from a CTs canner and various terminologies used in dose measurement.

Scanner radiation output

It is represented by volume CT dose index ($CTDI_{vol}$) [5]. It measures radiation output from a scanner in a very standardised way using a pair of standardised acrylic phantoms. It is measured from one axial CT scan (one rotation of x ray tube). The head and body phantom measures 16 cm and 32 cm in diameter respectively with a length of 14cm.

Its SI unit is mili-gray (mGy). It is a useful indicator of the radiation output for a specific exam protocol. However, it is important to know that it is not a direct measurement of patient dose.

Dose length product (DLP): It represents the overall energy delivered in a complete scan acquisition [6]. DLP (mGy-cm) = $CTDI_{vol}$× scan length (cm)

Implication: $CTDI_{vol}$ can be same in abdomen only or abdomen -pelvic CT scan. But DLP is more in the latter type.

Effective dose (E): It is a concept that reflects the stochastic risk (cancer induction) to a given patient. It is not a measurement of dose [7,8].

It is a quantity representing a whole body equivalent dose that would have a similar risk of health determinant as that due to partial body irradiation. It allows an approximate comparison of risk among different types of examination. It is expressed in mSv (millisievert) (Table 1).

Table 1

Region of Body (Adult)	K
Head/Neck	0.0031
Head	0.0021
Neck	0.0059
Chest	0 .014
Abdomen	0.015

E=DLP (mGy-cm)×k (mSv/mGy-cm), where k is a region-specific coefficient which depends on the region being scanned also called tissue weighting factor [9]. Value of k for an adult is given below. K values for different ages can be found from ICRP (The International Commission on Radiological Protection) Publication 103 [9].

Relationship between Image Quality, Radiation Dose and Nose

Quality of CT image can be described by several metrics [4] (Table 1).

I. Noise- describes the variation of CT numbers or Hounsfield units in a physically uniform region

II. SNR (signal to noise ratio)

III. CNR (contrast to noise ratio)

Simply put, as Radiation dose↑, noise↓, but image quality↑

The principle is that radiation dose should only be reduced under the condition that the diagnostic image quality is not compromised. The first task is to appropriately define the target image quality for specific Examination not requiring higher spatial resolution or lower noise.

Implication

In high contrast situation like in CT colonography where we want to detect polyps from a background of bowel gas and contrast-tagged stool, noise level can be allowed to remain high with reduction of dose without hampering diagnostic confidence [10,11]. Likewise, in low contrast situation as in CT scan of brain, liver or pancreas, noise must be low for detection and optimal characterisation of lesion [4]. The second task is to improve image quality i.e. to reduce image noise by optimising CT system, scanning techniques, improving image reconstruction and data processing [4].

General Strategies for Dose Reduction

Optimisation of CT system

Detector: Solid state detectors are now widely used instead of ionisation chamber detectors because of higher detective quantum efficiency (DQE) of the former. The DQE describes how effectively an x-ray imaging system can produce an image with a high signal-to-noise ratio (SNR) relative to an ideal detector. If a system DQE is increased, required radiation exposure to a patient can be decreased for the same image SNR and exposure conditions. Detectors with rapid response and low afterglow are desirable to allow faster scanning speed and high image quality with reduced dose [4,12].

Collimators: Pre patient collimator (between x ray source and patient) regulate size and shape of x-ray beam. Closely collimated beam leads to exposure of limited area avoiding unnecessary radiation dose to patient. Secondly, well collimated beam produce less scatter radiation, thus improving image quality [4,13].

Post patient collimators (between the patient and the detector) reject scatter radiation which improves image quality but sacrifices dose efficiency. Hence a trade-off is needed in designing scatter-rejection collimators [14].

X ray beam shaping filter: Filters are devices for absorbing low energy radiation which does not contribute to image formation, but gets absorbed by the patient. In other way, filters harden X ray beam (increase mean energy). Special shaped filters e.g. bow tie filters reduce the x-ray intensity in the peripheral region of body, thus reducing skin dose. Different types of filters for different applications are available now for example adult head, adult abdomen, and paediatric and cardiac filters [15,16]. It is important that patient be properly centred to avoid underexposure of central region and overexposure of peripheral region [17].

Scan range: Keep scan range as small as possible but as large as necessary.

Technique charts (Fixed tube current): It allows operators to select appropriate mAs (milliampere-second) as a function of patient size [18,19]. Since radiation dose increases with increase in mAs, it has to be kept low, but not as low to produce noise and degrade image quality. Since, tube potential (kV) is usually kept low for better contrast and exposure time (sec) is kept low

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for reducing motion artefacts, tube current (mA) is adapted to patient size. Children and small adult need lower mA as compared to larger patients. For obese patients tube current (mA), and the tube potential (kV) has to be increased for sufficient exposure.

Tube current (mA) modulation

Principle: since patient's body is not uniform, there is large variation in absorption of x ray both with projection angle and anatomic region. Data acquired through body part having less attenuation can be acquired with substantially less radiation exposure and without negatively affecting image noise [3,4,20,21].

Angular (X,Y) mA modulation: it addresses the differences in attenuation around patient by modulating tube current as the x-ray tube rotates about the patient between AP and lateral projection.

Longitudinal (z) mA modulation: it addresses the variation in x ray attenuation along Z axis of patient (shoulder to abdomen for example) by varying mA.

Combined (both angular and longitudinal mA modulation): dose is adjusted according to patient attenuation in all three dimensions. (most comprehensive approach)

Automatic exposure control (AEC): It is an advanced technique currently available on scanners. Which adjusts tube current in real time in response to x ray intensity at the detector [22,23]. It can reduce dose up to 40%. It is vendor specific. e.g. General electric (GE) uses Auto Ma AND Siemens CARE Dose4D for AEC.

Optimal kV (tube potential)

Principle [3,4,24-26]:

A. Low kV will produce high contrast but increase radiation dose to the patient.

B. Iodine has increase attenuation (CT contrast) at lower tube potential than at higher tube potential. Hence with lower kV superior enhancement occurs with the use of iodinated contrast media.

C. Noise increases with lower kV. So, trade-off between noise and contrast enhancement is to be done.

D. Iodine attenuation (CT number), image noise and contrast to noise ratio varies according to patient size. For small sized patient (children), noise levels remain almost the same with different kV. But with large sized patient (obese), noise is significantly higher and contrast to noise ratio is low at low kv.

E. For noncontract CT, benefit of using lower kV is not established.

F. Therefore, always uses an optimum tube potential (not necessarily lower) yielding best image quality considering all above factors. This optimal tube potential is dependent on patient size and specific diagnostic task.

Examination and Patient Specific Dose Reduction Strategies

Paediatric patients [25,27]: Risk of cancer is 2-3 times higher than adults

i. Avoid unnecessary CT examinations.

ii. Use alternative modalities like USG or MRI if necessary diagnostic information can be obtained from them

iii. Avoid multiphase examination (noncontrast, arterial, venous, delayed etc.) if information can be obtained from single-phase scan

iv. Use automatic exposure control (AEC), technique charts, child size bowtie filter, small field of view.

v. optimum tube potential and lower tube current

vi. High helical pitch and fast rotation time for avoiding motion artefacts.

Pregnant patients: Usually CT scan is indicated for suspected appendicitis, pulmonary embolism and urinary tract calculi.

A. Strategies

I. Alternative non-radiation based imaging modality if possible and postponing scan until after deliver if not urgently required

II. For appendicitis- USG is the best modality, avoid multiphase CT. Scan volume to be restricted to necessary anatomy [28]

III. For detection of renal calculi- low mas, high pitch, limited scan range [29]

IV. For abdominopelvic CT- wider beam collimation, higher pitch, lower mAs, kV and scan range

Cardiac CT: Cardiac CT has inherent high radiation dose because of use of relatively high mas and low pitch values for improving temporal and spatial resolution. Dose is proportional to mAs/pitch.

A. Strategies

i. ECG based tube current modulation- it involves modulating tube current down to 4-20% of the full tube current for phases that are of minimal interest (i.e. during systole). The percentage of dose reduction is higher with slow and regular heart rates as R-R interval is higher at slow heart rate. Up to 64% dose reduction can be achieved without sacrificing image quality Hence use of β-blocker is indicated. It is not useful for irregular heart rate as it compromises image quality [30].

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ii. Prospective ECG gating (step and shoot acquisitions) [31]: Here X-ray is turned on at the preselected phases during the cardiac cycle unlike retrospectively ECG -gated mode where the x-ray beam is continuously on.Due to lack of overlapping beams at lower spiral pitch, it is very dose efficient. But the disadvantage is it is more susceptible to deterioration of image quality due to motion artefacts and cine sequences (depicting heart motion) cannot be generated unlike from retrospectively ECG-gating data. It needs stable and low heart rate.

iii. Dual source CT scanners allow for a gapless acquisition with a pitch of up to 3.4 which cannot be achieved with conventional single-source CT scanners. High pitch and ECG based tube current modulation can decrease dose up to 50% as compared to 64 slice scanners [32].

iv. Use of cardiac bow-tie filter.

Dual Energy Ct [33,34]:

i. There is no increase in radiation exposure when dual-source dual energy CT technology is used instead of single-energy techniques.

ii. It allows creation of virtual non-contrast images from a post contrast DECT dataset, thus obviating the need for prior non-contrast scanning with substantial beneficial impact on the overall radiation dose associated with the exam. But image quality of virtual noncontract CT has high noise level.

iii. It is especially useful for patients who require frequent follow-up CT examinations. E.g. follow up of aortic stent grafting [35].

CT Perfusion

Radiation dose is usually higher than routine CT scan because of long scanning time. Special filtering techniques which reduce noise are HYPR-LR (highly constrained back projection local reconstruction) and MBF (multiband filtering) [36]. Animal model has shown tenfold dose reduction in renal perfusion CT (80 kV, 160mAs to 80 KV 16 mAs).

Interventional CT [37,38]:

i. Optimising scanning technique in CT fluoroscopy (lowering kV, mA and exposure time, increasing slice thickness and limiting the scan range to only necessary anatomy).

ii. Intermittent or quick check mode than continuous mode.

iii. Proper shielding garments (lead apron, thyroid shield and leaded eyeglasses), needle holders to reduce direct exposure to hand.

iv. Shielding adjacent to the scanning plane (171) to reduce scatter radiation.

v. With increased operator experience, exposure time gets reduced.

Future prospective

Iterative reconstruction: It improves image quality and reduces radiation dose in CT than conventional filtered back projection (FBP) techniques. It can reduce image artefacts such as beam hardening, windmill and metal artefacts. Iterative reconstruction is also superior to filtered back projection in handling insufficient data. It is expected that iterative reconstruction will be implemented into clinical practice in the near future [39].

Photon-counting detector: Current clinical CT scanners use “current mode” type of detector. Photon counting detectors/ pulse mode detectors are research interests [40]. These detectors count each photon and record its energy individually so that information can be detected and discriminated on a photon-by-photon basis. A dedicated photon-counting digital mammography system is already commercially available. It is expected to have photon counting-based clinical CT available soon.

Dynamic Bowtie Filter for Cone-Beam/Multi-Slice CT: It is largely a research interest. The attenuation profile it produces can be adaptively changed with the gantry rotation further reducing dose [41].

Selective In-plane Shielding [3,42,43]: Selective shielding of radiation sensitive tissues and organs such as eye lens, thyroid, or breasts can be done during brain, cervical spine, or chest CT scan respectively. Shields made of thin sheets of flexible latex impregnated with bismuth are used. For each organ, dose reduction is accompanied by increased noise and artefacts. The artefact on the reconstructed images can be minimized by keeping the distance between the shielding and the organs >1 cm. however, it has not come to wider practice.

Conclusion

Whatever CT dose reduction strategies are to be followed, ALARA (As Low as Reasonably Achievable) principle is a must. Considering tremendous benefit of CT scan and potential risk associated with it, a risk-benefit assessment should be done in each patient. Certain group of patients (e.g. pregnant, children) need special dose reduction strategies.

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