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Do No Harm. Efforts and methods for radiation dose reduction in medical imaging

Prelude. *The goal of this article to give the reader an overview about the current efforts and methods for reducing the dosage of possibly harmful ionizing radiation patients are exposed to during medical imaging examinations. Since the largest amount of radiation (among imaging techniques today) is used during Computed Tomography, the main focus of this article is CT.*

The need for conscious dose management. Radiation (or X-ray) can be a very powerful diagnostic tool in the hands of physicians, however the same radiation is a major risk factor for developing cancer.

There are several scientific units to measure radiation, such as “rad”, “grey” or “roentgen”. However the most commonly used in the field of medical imaging is “sievert” (Sv) or “millisievert” (mSv). This is the unit of the effective dose of ionizing radiation, which accounts for the relative sensitivities of different tissue and organs of the human body.

According to estimates, the average effective radiation exposure of a person from natural sources (for example cosmic background radiation) is around 3 mSv per year. This figure however is highly inaccurate, and can change according factors like the geographical location, altitude above sea level and radon gas in homes [4].

The reason CT examinations are the main focus of this article, is the difference in the amount of radiation they deliver to the patient’s body compared to X-ray scans. See Table 1.

Table 1. Radiation exposure in different examinations [5]

Examination Type	Radiation exposure (mSv)
X Ray - Extremity	0,001
X Ray - Chest	0,1
CT - Head	2
CT - Chest	7
CT - Abdomen	10
CT - Cardiac Angiography	12

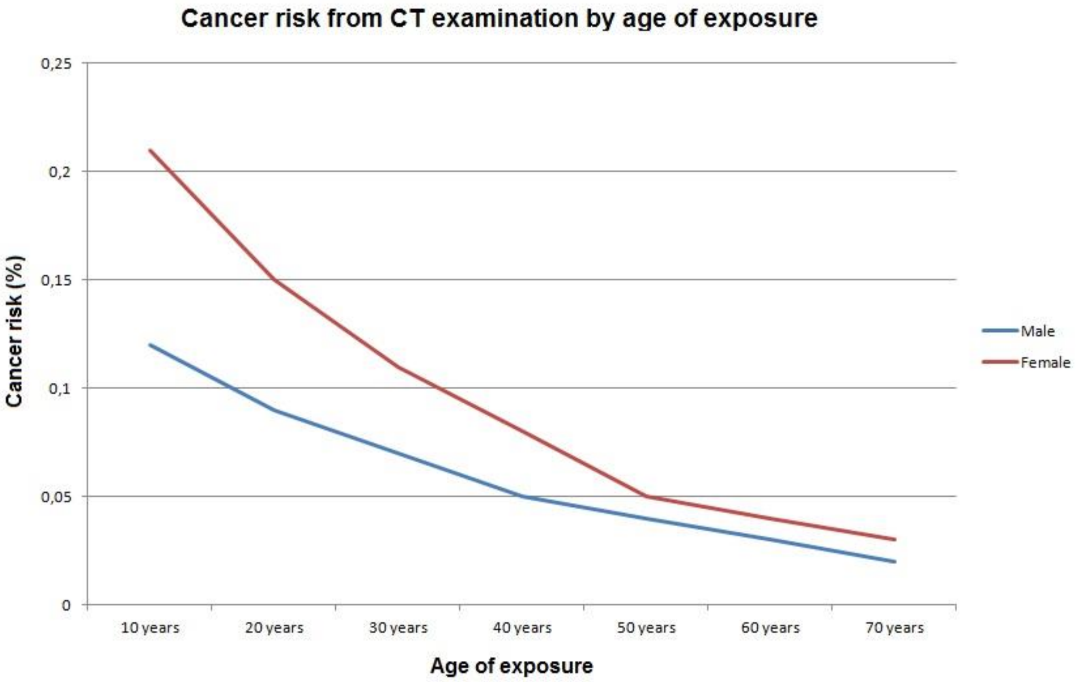

Fig. 1. Cancer risk of a CT Abdomen scan

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In case of a poli-trauma patient (for example someone who suffered a serious car accident), to discover possible life-threatening injuries that require immediate surgery, it is justified to use a whole-body CT scan. However exposing a patient to this amount of radiation, to diagnose a mildly serious chronic condition, or during a likely negative screening examination, is clearly not justified.

Special care should be taken in case of pediatric CT scans, since the risk of developing cancer is greater with earlier age of exposure in patients.

For example let's examine the cancer risk a CT examination poses at different age of exposure. Based on the data from the National Research Council [6] see in Figure 1 the risk of cancer due to a CT Abdomen scan (average 10 milliSv of radiation) in males and females of certain age groups.

There are several possibilities to achieve dose reduction:

– alternative imaging modalities with less or no ionizing radiation
– reducing radiation dose with proper optimization and customization of scan protocols, if a CT exam is absolutely necessary
– improved CT machines that deliver lower doses of radiation while maintaining image quality.

Alternative: Radiography (X ray). As it is clear from Table 1, radiography exposes the patient to 1-2 order of magnitude less radiation than CT scans. Also with lots of indications the 3D capabilities of the CT do not give substantial increase in the chance of a correct diagnosis compared to a conventional x-ray [10]. Therefore when a conventional x-ray examination is sufficient to establish the diagnosis, it should be the preferred method.

As an exception fluoroscopy should be mentioned. Fluoroscopy uses continuous radiation to obtain real-time moving images of the internal structures of a patient. Although it is considered to belong to the field of conventional radiography, the absorbed dose of patients is in the range of CT scans, therefore the risks and benefits to the patient should be carefully considered.

Alternative: Ultrasonography (US). Obviously when not clinically indicated, not performing a CT examination is the best radiation dose reduction strategy. For diagnosing some conditions a possible alternative to CT can be ultrasound. Ultrasound machines do not expose the patient to any ionizing radiation, therefore can be widely used for patients with high risk factor, such as pregnant women and children. Ultrasound is also proved to be an effective method for diagnosing muskoskeletal (MSK) pathologies. Studies [2] show that the use of ultrasound in MSK cases increased 500% from 2000 to 2009. The reasons behind this increase (apart from the fact that US use no radiation) are the relatively low cost (about 15% of a CT scanner) and ready availability of the technology. Also many non-radiologist physicians are familiar with it.

Alternative: Magnetic Resonance Imaging (MRI). As ultrasonography, MRI examinations do not expose the patient to ionizing radiation. Also MRI can achieve better contrast in soft tissue imaging, therefore it is the most promising alternative to CT.

However the higher price of MRI machines make them less prevalent in the clinical environment. The price of a CT scanner is in the 100.000 – 300.000 $ range while an MRI machine costs about 1.000.000 – 3.000.000 $.

Reduction methods: Customize Scan protocol for patient. Based on studies [5] it is clear, that the largest effective radiation dose among CT examinations is delivered in case of chest and abdomen scans (see Table 1). The reason for this is that the soft tissue and vital organs of these areas are much more sensitive to ionizing radiation than the musko-skeletal system of the extremities. Therefore the main targets of the dose reduction efforts are these examinations.

The main parameter, that radiologists should carefully calibrate when setting up a scan, is tube voltage. The tube voltage (or tube potential, measured in kilovolts, kV) effects both the energy and the quantity of the photons generated by an X-ray tube.

The commonly accepted baseline tube voltage for an adult patient is 120 kV. However studies [1, 7] show that it is possible to significantly reduce the tube voltage based on the patient's Body Mass Index (BMI) without compromising image quality. In case of non-obese patients (BMI less than 30 kg/m^3) only 100 kV is needed, while with patients whose BMI is less than 20 kg/m^3 even 80 kV is often acceptable. The reason for this is that body fat affects the x rays traveling through the body and lowers image quality.

Since the radiation dose is related to the square of the tube voltage, the decrease from 120 kV to 100 kV, with all other imaging parameters held constant, can result in 31% reduction of dose. Also lower energy photons interact more strongly with iodinated contrast materials, that results in better contrast of the blood vessels with the surrounding soft tissue.

The current of the x-ray tube (expressed in milliAmpers, mA) is also an important parameter. It affects the quantity of the photons generated. However setting up the current and voltage of the x-ray tube for the whole scan is not the only option. Many CT scanner manufacturers include an automatic tube current modulation (TCM) function guided by the ECG monitor. See Figure 2 for illustration. In this example the delivered radiation is proportionate to the area under the curve. Different imaging techniques are compared:

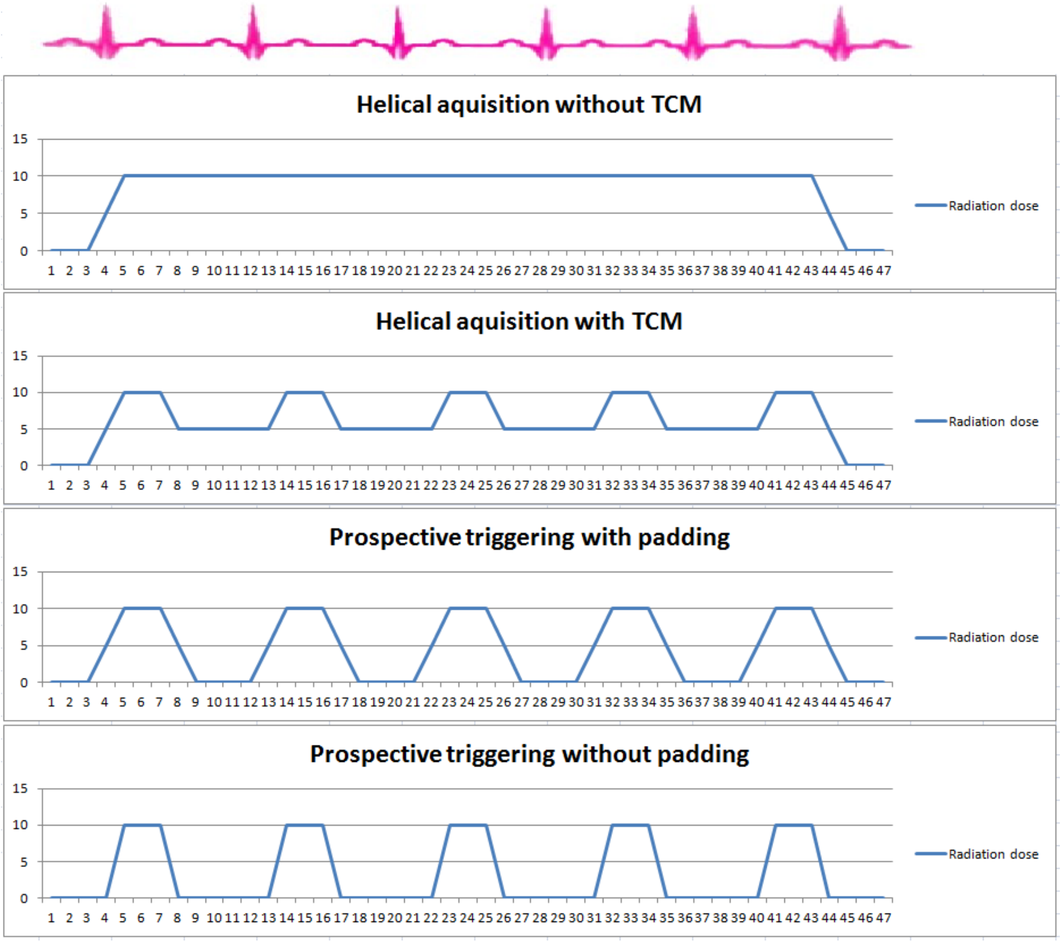

Fig. 2. Radiation dose of reduction techniques in the cardiac cycle

The motion of the heart during the cardiac cycle distorts images. Several techniques are used to counteract this. The first is retrospective gating (Figure 2, graph 1). With this method, the radiation is constant and the created image data is filtered after the acquisition based on the ECG. Only images created during the late diastole period are kept, the rest are deleted. It is clear that using this method exposes the patient to radiation even in timeframes when diagnostically relevant data is not obtained at all.

With ECG guided TCM, the radiation dose can be reduced in periods of the cardiac cycle when acquisition is not needed (Figure 2, graph 2).

However the above described method can only be effectively used when the patient’s heart rate is stable and most effective when the heart rate is low. In these cases a dose reduction of 25% is achievable. In case of fast heart rate or irregular rhythm this technique is not recommended.

Another approach to reducing the radiation dose the patient is exposed to, is reducing the time the x-ray source is active. To achieve this modern CT machines use pulses of radiation (by modulating the tube current from zero to peak amperage) instead of continuous output. This method is combined with prospective triggering guided by real-time sampling of the patient’s ECG, to anticipate the optimal phase of the cardiac cycle (when the heart is motion-free). Since this optimal acquisition window is very short(usually around 200 milliseconds), the total exposure time can be reduced by over 60% (See Figure 2, graph 3).

By default most CT scanners implement a short additional acquisition time before and after the optimal window, called “padding” as a precaution against irregularities in the heart rate. However the radiologist can override this setting, and for patients who have good heart-rate control (lower than 60 beats-per-minute) padding can be reduced, or for even lower rates (less than 55 beats-per-minute) it can be completely eliminated without compromising image quality [1]. This has the potential to reduce exposure time further (See Figure 2, graph 4.)

These techniques can significantly reduce the radiation dose of the patient but radiologists have to carefully consider the implementation so they do not compromise image quality. If the resulting images are not usable for a diagnosis, the scan may have to be repeated, making all dose reduction efforts futile.

Iterative reconstruction algorithms. Reconstruction is the mathematical method for transforming raw CT data (series of measurements of absorbed radiation by the detector of the scanner) into the CT images or 3D models that can be visualized. Over the last decade several so-called Iterative Reconstruction (IR) techniques have been developed and becoming widely used. These methods vary greatly, and their mathematical basis and detailed description is beyond the scope of this article. The reason they are mentioned is that these algorithms can reduce the noise in the reconstructed images, so the radiologist can reduce the radiation dose used in the examination (by lover tube voltage and current), and still acquire images with comparable quality. Studies [1] vary in the achievable dose reduction, but a 25% decrease is usually possible.

Extremity CT Scanner. (Figure 3) An opportunity to reduce radiation dose in orthopedic imaging is the use of dedicated extremity CT scanners

Fig. 3. Extremity CT Scanner

These devices usually utilize cone-beam CT (CBCT) technology for imaging of peripheral skeletal fractures and disorders.

Images are acquired using a short X-ray pulse instead of continuous radiation, resulting in a radiation dose of up to ten times lower compared to extremity imaging protocols with conventional CT [2]. The smaller gantry size plays a role too: since the x-ray source and the detector are much closer to each other, lower energy photons are adequate to produce good quality images.

Also the gantry can be positioned horizontally, allowing weight-bearing 3D scans of a standing patient, which is not possible with conventional CT scanners.

Dedicated extremity CTs usually have smaller price, installation and maintenance costs than a full-sized scanner, so high proliferation is expected for this relatively new technology.

Future innovations: Inverse Geometry CT. Vendors continuously research new technologies to reach improvements in computed tomography. One of the proposed approaches to further reduce radiation dose and improve image quality is the so-called Inverse-geometry CT. In a conventional CT scanner the x-ray source emits from a small spot, and measured by a large-area detector, resulting in a large, cone-shaped beam (see Figure 4).

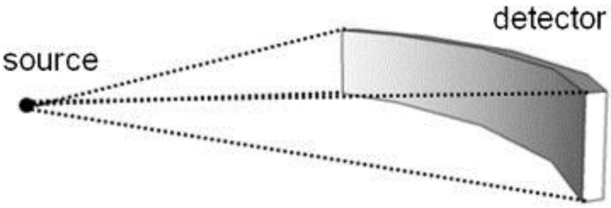

Fig. 4. A conventional cone-beam CT

Because of this, the measured data needs to be corrected to eliminate the distortion of the cone-shaped projection. Also the entire target object is irradiated throughout the acquisition process.

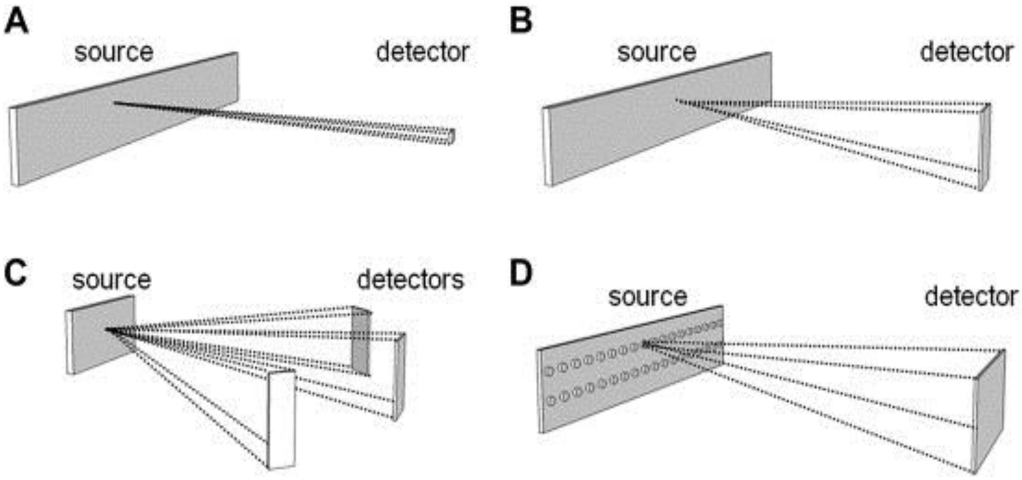

Fig. 5. Proposed inverse-geometry CT concepts

Inverse-geometry CT proposals presume a larger x-ray source composed of multiple spot-like emitters and smaller detectors. Theoretically this would eliminate the cone distortion and also reduce the radiation received by the patient, because the emitters would only be active for a short time each and produce much narrower x-ray beams (see Figure 5.).

While the feasibility of this technology was demonstrated [9] with phantom and animal experiments, a considerable amount of testing and development is needed before it can be used in a clinical environment.

Conclusions. While CT is a powerful diagnostic tool, we should not forget the old saying: "When you have a hammer, everything looks like a nail". Radiologists should always consider the risks and benefits before performing examinations that expose patients to radiation, and make sure that the procedure is justified.

As it was demonstrated, with proper clinical decision-making and the professional and conscious use of customizable scanning protocols on a case-by-case basis, it is possible to reduce the radiation dose patients receive during diagnostic imaging examinations. This way we can minimize the risk of later cancer induced by ionizing radiation.

This article, while thorough, is by no means exhaustive. Interested readers are encouraged to seek out more comprehensive studies of this topic in the rapidly evolving field of medical diagnostic imaging.

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