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Radiological protection in computed tomography and cone beam computed tomography

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Abstract–The International Commission on Radiological Protection (ICRP) has sustained interest in radiological protection in computed tomography (CT), and ICRP *Publications 87* and *102* focused on the management of patient doses in CT and multi-detector CT (MDCT) respectively. ICRP forecasted and 'sounded the alarm' on increasing patient doses in CT, and recommended actions for manufacturers and users. One of the approaches was that safety is best achieved when it is built into the machine, rather than left as a matter of choice for users. In view of upcoming challenges posed by newer systems that use cone beam geometry for CT (CBCT), and their widened usage, often by untrained users, a new ICRP task group has been working on radiological protection issues in CBCT. Some of the issues identified by the task group are: lack of standardisation of dosimetry in CBCT; the false belief within the medical and dental community that CBCT is a 'light', low-dose CT whereas mobile CBCT units and newer applications, particularly C-arm CT in interventional procedures, involve higher doses; lack of training in radiological protection among clinical users; and lack of dose information and tracking in many applications. This paper provides a summary of approaches used in CT and MDCT, and preliminary information regarding work just published for radiological protection in CBCT.

Keywords: Computed tomography; Cone beam CT; Radiological protection; Patient dose; Radiation protection of patient

This paper does not necessarily reflect the views of the International Commission on Radiological Protection.

1. COMPUTED TOMOGRAPHY

Computed tomography (CT) is a unique imaging technique that has been growing in usage, particularly since the development of multi-detector CT (MDCT) which enables faster and higher resolution scanning. CT technology has been improving continuously, providing images of superb quality in two-, three-, or four-dimensional format. Back in 1998, there were no cases of skin injuries from CT examinations, and there was little interest in cancer risk estimate from CT scans. Instead, manufacturers were mainly competing with each other in terms of reducing scanning time rather than patient dose, as customers rarely asked about the radiation dose. At that time, the International Commission on Radiological Protection (ICRP) warned that the use of CT was increasing and there was potential for both single CT scans and repeat CT scans to result in high patient doses (ICRP, 2000; Rehani, 2012). A recent article summarised how the actions by ICRP and others led to an era of serious consideration of patient dose reduction in CT examinations, and competition among manufacturers to reduce the doses delivered by CT machines (Rehani, 2012). The article also summarised justification and optimisation principles of ICRP, as applied to CT scanning, as well as actions taken by the International Atomic Energy Agency (Rehani, 2012). The current paper summarises approaches used by ICRP in radiological protection in CT, and recommendations on radiological protection in cone beam CT (CBCT) which have been published recently (ICRP, 2015).

1.1. Approach to safety

Safety is best achieved when it is built into a system, rather than made optional for users. Realising this approach, *Publication 87* (ICRP, 2000) emphasised the actions that manufacturers may take on new features in CT equipment that can help users to manage patient dose. The best example of this approach is a 'collision avoidance system', which started within the automobile industry but has now been implemented in medical imaging equipment. If the gantry of the imaging machine just touches a person, the gantry immediately stops moving. When collisions have to be avoided through education, training, and instructions, the results cannot be the same. Both detection of the problem and avoidance of the effect should be automatic. Similar safety approaches have been implemented in the last decade through CT manufacturer use of automatic exposure control and tube current modulation to reduce patient radiation dose. In each rotation of the x-ray tube around the patient, the system detects attenuation and adjusts exposure automatically to achieve optimisation in dose and image quality. Technology holds the key to future advances in safety and optimisation of protection (Rehani and Vañó, 2011; Rehani, 2013).

1.2. Shift in emphasis from dose management to avoidance of overexposure

Between 2001 and 2007, the emphasis of radiological protection in CT was on management and optimisation of patient doses (ICRP, 2007a). Many publications used potential risk of cancer in CT exposure to draw attention to justification of exposure and optimisation of radiation protection. However, since the invention of

CT in 1972 until 2007, CT machines performed well across the world. Accidental overexposure resulting in radiation-induced skin injury, whether as a result of operator error or machine error, had not been reported. One report of temporary hair loss in CT brain perfusion [and digital subtraction angiography (DSA)] in 2005 was not attributed to error (Imanishi et al., 2005), but was attributed to overexposure that can potentially result in a typical situation.

In October 2009, the media highlighted a report of skin injury from overexposure to a child in 2008 due to operator error (Bogdanich, 2009). The report included information about administration of up to eight times the normal radiation dose to 206 possible stroke victims over an 18-month period during a procedure intended to obtain clearer images of the brain. The US Food and Drug Administration (FDA) in 2009 issued an initial notification regarding a safety investigation of facilities performing brain perfusion CT scans This alert indicated that US FDA had become aware of radiation overexposure during perfusion CT imaging performed to diagnose stroke at a single, particular facility. The incident reported above involved brain perfusion CT, which may be more prone to substantial radiation overexposure if performed incorrectly due to the cine nature of the acquisition.

US FDA has been working with the Medical Imaging and Technology Alliance on standardised dose reporting. The purpose is to ensure that necessary dose and patient information (e.g. size and age data) for x-ray imaging procedures are recorded in Digital Imaging and Communications in Medicine radiation dose structured reports, so they can be easily transferred to a dose registry.

To develop standards that define safeguards to help prevent CT scanners from delivering excessive radiation, the National Electrical Manufacturers Association and US FDA have collaborated to create new software called the ‘Computed Tomography Dose Check’. The CT Dose Check notifications and alerts call the user’s attention to what may be high-dose settings, and offer a ‘time-out’ opportunity for the user to confirm or change scan settings before proceeding. Further, there is a pop-up box that requires the user to type in their initials when over-riding the standard protocol. All new CT equipment must have this safety device.

In Europe, the Heads of the European Radiological Protection Competent Authorities have signed a Memorandum of Understanding with US FDA to share information on promoting radiation protection in CT imaging.

2. CONE BEAM CT

CBCT is a form of x-ray CT in which the x rays, in the form of a divergent cone, illuminate a wide-area detector for image capture. While conventional MDCT scanners acquire consecutive tomographic slices, in CBCT, two-dimensional projection images are acquired by an area detector and directly reconstructed into a three-dimensional dataset. Although first introduced in 1982, multiple teams in the 1990s worked to bring the system to a level of clinical utility that only gained popularity in the 2000s.

CBCT represents an emerging technology that enables high-resolution volumetric scanning of the anatomy under consideration. Just as in MDCT, use of CBCT is increasing steadily in clinical practice. Although it is a relatively new modality, CBCT is being used for a variety of clinical applications such as dental imaging, head and neck imaging (including sinus CT), high-resolution bone imaging, and intra-operative and interventional imaging. Mobile units represent a fast growing use of CBCT.

CBCT is also used in radiotherapy for pretreatment verification of patient position and target volume localisation.

In view of initial usage of CBCT in dental imaging, where doses were tiny, users are tempted to see CBCT as 'light' CT or consider it as 'low-dose CT'. However, at present, CBCT use, even in orthodentistry, can result in relatively high doses to the thyroid and lens of the eye. CBCT is widely used as C-arm mobile units for interventional applications, with much higher radiation doses that equal or exceed those from MDCT. As CBCT is a relatively new development in clinical practice, radiation doses and possible effects of CBCT are still being gathered and analysed. These units are poorly understood, with little or no training provided to the users, and poor dose tracking. Even at this early stage, however, studies indicate that there is room for optimisation to keep the radiation dose as low as reasonably achievable.

ICRP has produced a document on radiological protection issues in CBCT, and developed guidelines and recommendations (ICRP, 2015).

2.1. Differences between standard MDCT and CBCT

CBCT systems differ from 'standard' MDCT systems in several ways that affect image quality and radiological protection. Some key differences are listed below.

- Due to the cone beam nature of the irradiated field, and the associated non-uniformities in the primary and scatter radiation imparted to the scan volume, the standard dose metrics popularised by MDCT cannot be applied to CBCT.
- CBCT systems have superior spatial resolution for high-contrast objects (e.g. bone, lung), but inferior contrast resolution for low-contrast objects (e.g. soft tissue). A CBCT user can significantly influence the radiation dose imparted to the patient by judiciously deciding whether a 'high-dose' scan is needed, or if a 'low-dose' scan will suffice. A 'high-dose' scan is generally needed if soft tissue structures are the main diagnostic focus. A 'low-dose' scan may be sufficient for angiographic scans with arterial or venous contrast media, or for defining the position of interventional catheters.

2.2. Radiological protection in CBCT

2.2.1. Radiological protection of patients

Any attempt to match image quality of a thin-slice CBCT with a thick-slice MDCT will result in excessive dose.

In many CBCT scanners, the angular span over which the projection data are acquired can be customised. Most interventional and intraprocedural C-arm CBCT systems can scan an angular range spanning 180–240°, plus the cone angle of the x-ray beam. This allows keeping radiation-sensitive organs, such as the thyroid, eyes, female breast, and gonads, on the 'detector side' of the arc in order to achieve protection of these organs. The user should take advantage of this feature of CBCT, which is generally not available in MDCT.

The Commission in its *Publication 129* (ICRP, 2015) has recommended the provision of alerts when the dose is higher than specified, and has stopped exposure at levels that should not be exceeded.

Further recommendations include regular and continuous monitoring of radiation output throughout the examination, comparison with reference or desired levels, and provision of feedback to the system with automatic adjustment.

To date, as elaborated above, the radiological protection emphasis has been on dose management and, more recently, on avoidance of high-dose accidental exposures. However, there is another aspect that requires consideration in CBCT: risk management.

Many patients undergoing interventional procedures using CBCT are over 50 years of age, where the risk of stochastic effects is of lower consequence. Kothary et al. (2011) studied the impact of C-arm CT on radiation exposure of patients with hepatocellular carcinoma treated by chemoembolisation. They indicated that routine use of C-arm CT can increase stochastic risk, but decrease deterministic risk from DSA. The increase in stochastic risk is operator dependent; as such, with experience, it can be reduced. C-arm CT provides information that is not provided by DSA in many patients, while decreasing the use of iodinated contrast medium. Therefore, Kothary et al. (2011) recommended replacing DSA with C-arm CT based on risk management considerations.

Currently available CBCT scanners are not able to provide dose values in standardised dose indices for machine outputs or patients. There is a need to develop consensus and bring uniformity in CBCT dosimetry. Moreover, equipment used for both fluoroscopy and CBCT presents new challenges in dosimetry, and there is a need to develop methods that aggregate exposures to individual patients during entire procedures.

2.2.2. CBCT optimisation

Some points for consideration of future development are: collimation should not exceed detector size; laser guidance of needles in interventions; and minimisation of dose wastage by mechanical components.

ICRP provided recommendations dedicated to education and training in *Publication 113* (ICRP, 2009), and these are also applicable for CBCT. Essentially, the concept holds that 'the level of training in radiological protection should be commensurate with the level of expected radiation exposure'.

All personnel intending to use CBCT for diagnostic purposes should be trained in the same manner as for corresponding applications in diagnostic fluoroscopy and CT. All personnel intending to use CBCT for interventional purposes should be trained in the same manner as for interventional fluoroscopy and interventional CT.

2.2.3. Radiological protection of workers

Occupational radiation exposure is expected to be small in the case of clinic-based CBCT systems. When using a C-arm or other CBCT devices in an interventional suite or operating theatre, physicians, technologists, and other staff can protect themselves by using shielding devices. As required under national regulations in most countries, radiation workers must comply with regular individual dose monitoring requirements for managing radiation exposure, and keep a comprehensive dose record. Further, unless necessary, staff should move outside the fluoroscopy room when CBCT acquisition is taking place.

The principles of radiological protection of workers from ionising radiation are discussed in *Publication 75* (ICRP, 1997), in Paragraph 113 of *Publication 105* (ICRP, 2007b) and also in ICRP *Publication 120* (ICRP, 2013).

Interventionist physicians and other staff conducting CBCT should adhere to best practices in radiation protection, including use of protective shields and vests, maximising the distance from the x-ray source, and injecting contrast media using an automatic injector. While surgeons and interventionalists may be required to be close to the examined volume during two-dimensional fluoroscopy, patient condition permitting, all other staff should take extra shielding measures when acquiring CBCT scans. This may include leaving the room when possible, or using extra shielding when the clinical situation requires their presence in the room. The training of users, particularly those who use mobile C-arm and other mobile units with CBCT, has been covered in *Publication 129* (ICRP, 2015).

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