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The use of mobile computed tomography in intensive care: regulatory compliance and radiation protection

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Abstract

The use of mobile head computed tomography (CT) equipment in intensive care is of benefit to unstable patients with brain injury. However, ionising radiation in a ward environment presents difficulties due to the necessity to restrict the exposure to staff and members of the public according to regulation 8(1–2) of the Ionising Radiation Regulations 1999. The methodology for enabling the use of a mobile head CT unit in an open ward area is discussed and a practical solution given. This required the reduction in scatter doses through the installation of extra internal and external shielding, and a further reduction in annual scatter dose by restricting the use of the equipment based on a simulation of the annual ward workload.

1. Introduction

There are high number of adverse incidents [1] associated with transporting critically-ill patients outside intensive care [2, 3]. Neurologica Corp., (Massachusetts, USA), have developed a small mobile head CT scanner, the Ceretom™, for use within intensive care (ICU). This has the potential to improve patient safety by eliminating the need for the transfer of intubated and ventilated patients to fixed CT facilities. The Ceretom™ is controlled by a laptop via a wireless link; the gantry moving away from the patient on caterpillar tracks to obtain the head image. Both axial and helical modes are possible.

To estimate the feasibility of using the Ceretom™ in Plymouth Hospitals NHS Trust, Trust ICU staff collected data, (over a period of two weeks), on patients requiring urgent CT acquisitions. 85% had external ventricular drains or intracranial pressure (ICP) monitors, 95% had arterial lines, 85% had central lines, and 68% required one or more inotropic infusion. The median time for transfer to the fixed CT facility was 55 min (range 35–110 min) with

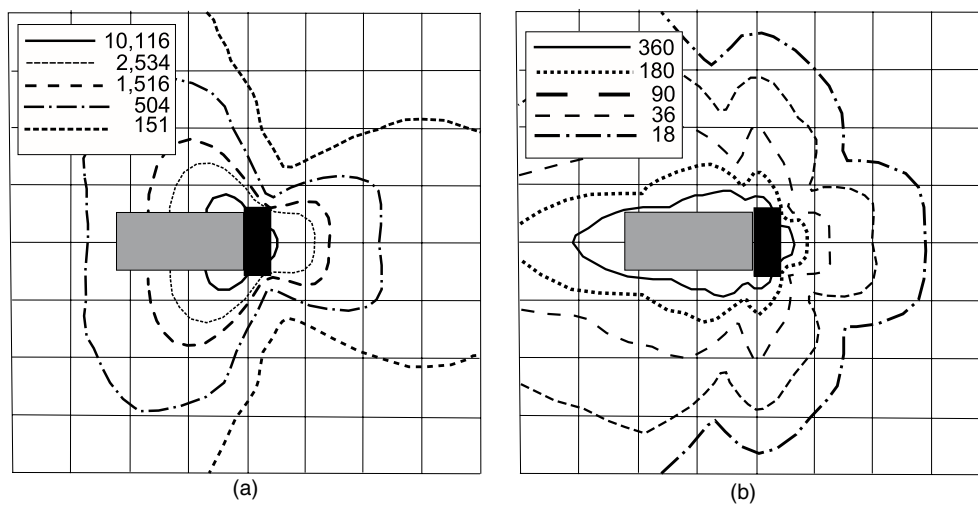


Figure 1. Figures showing the scatter maps before and after shielding modification. Both maps were acquired using the maximum tube rating (120 kV, 7 mA) with scatter rates given in $\mu\text{Sv h}^{-1}$, each square represents 1 m². (a) Diagram showing the original scatter map supplied by the manufacturer. (b) Diagram of the scatter map modified by the extra tube shielding and shadow shields.

ICP control being problematic during transfer in 16% of patients. One patient suffered a catastrophic airway event during transfer and ultimately died from chest sepsis. The three commonest causes of delay in obtaining acquisitions were unavailability of the scanner or anaesthetic staff, and portering delays. Following the publication by Masaryk *et al* [4], clinical staff at Plymouth Hospitals NHS Trust purchased a Ceretom™ for ICU. However, because the radiation protection approach in the UK varies considerably from that taken in the USA; especially with respect to dose constraints, it was not immediately clear whether the Ceretom™ could comply with UK legislation.

Examination of figure 1(a) shows the original manufacturer supplied scatter doses; these were considerable and due to the fact that a single acquisition was expected to take upwards of 1.5 min, would make working practices in the ward impracticable if a constraint of 0.3 mSv per annum were to be applied; this value being recommended by the NRPB as a planning constraint to indicate that the likely dose arising from new sources is restricted, and adopted in the Medical and Dental Guidance Notes (MDGN) [7]. Therefore, it was felt we could not comply with the Ionising Radiation Regulations (1999) (IRR99) [5] without either a modification to the Ceretom™, the use of a number of mobile radiation shields or a total evacuation of the ward; the latter two solutions being impractical due to issues over accessibility to patients and the general fragility of the patients in the ICU respectively.

The regulations covering the health and safety of workplace exposures from ionising radiation are IRR99; regulations 16 and 18 require the ability to control access and delineate the controlled area respectively: it was not clear how to comply with this without the use of mobile barriers; the use of which, was not conducive to good working practice. Regulation 11(1) clearly gives the radiation employer the responsibility for ensuring compliance with the dose constraint of 6 mSv for non-classified workers, and 1 mSv for members of the public, (excluding trainees). In order to constrain the exposure to workers, regulation 8 requires the radiation employer to restrict exposure as much as reasonably practicable (ALARP) using a hierarchy of control measures (regulation 8(2)). Regulation 31(1) imposes a duty on the

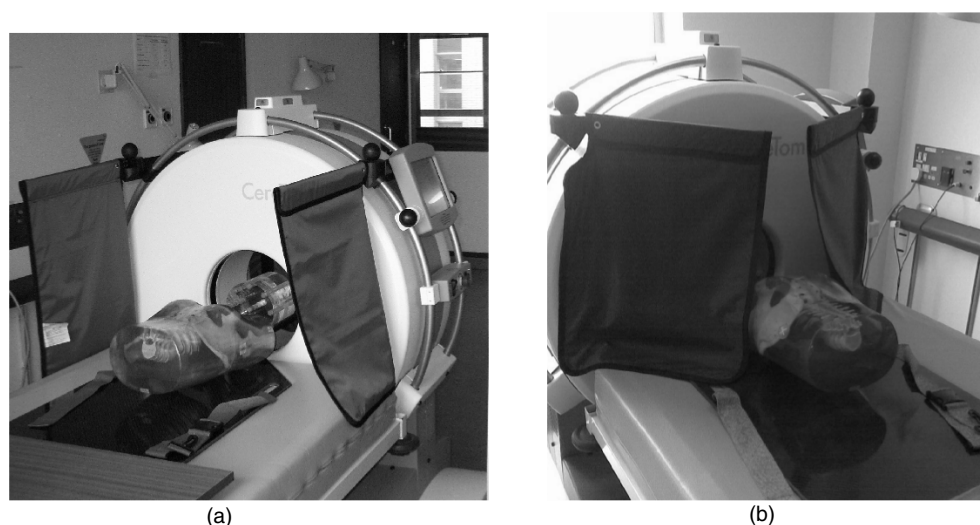


Figure 2. Photographs showing the Ceretom™ with (a) the configuration used to measure scatter using a CTDI head phantom and the pelvic phantom *in situ*, and (b) the shadow shield position during image acquisition, used to minimise scatter.

manufacturer to design equipment to ensure that exposures to patients, staff and members of the public are ALARP, and because of the differing national radiation dose limits, this is clearly not the case.

Additional guidance on the application of these regulations is given in the approved code of practice (ACOP) [6] which states: *if the device is designed for use in public areas, or where there is continuous access to the working area by employees or other persons not directly involved in the work, the shielding should be designed to reduce dose rates to the lowest level that is reasonably practicable. In this case, the dose rate should be so low that it is unnecessary to designate the area around the device a supervised area.* Consequently, it was felt that the Health and Safety Executive (HSE) would have to be consulted on the applicability of ACOP for this specific use as no amount of practical shielding would limit doses so low that a designated area would not be necessary.

2. Approach and discussion

In order to satisfy the regulations regarding restriction of exposure, external shielding was designed [8, 9]. The shadow shields are 0.5 mm lead equivalent aprons attached to the side of the Ceretom™ on a swivel that hangs down to limit scatter. The purpose of the swivel is to ensure quick access to the patient in an emergency, and limit the need for separate external mobile shields, while simultaneously still providing the ability to observe the patient during acquisition. In addition, another shadow shield of 1.0 mm lead equivalence was located at the back of the Ceretom™ to limit scatter in the head direction. Photographs of the shadow shields are shown in figure 2.

The shadow shields and internal shielding were installed by the manufacturer prior to shipment. The manufacturer produced scatter map was then verified using a CTDI phantom located centrally in the unit's bore as the attenuation/scatter medium. However, these standard measurement conditions do not account for the scatter and attenuation characteristics that the

human body would produce. Because the Ceretom™ was to be used in an open ward, it was felt that some account for the effect of the body on the scattered radiation should be included.

In order to obtain realistic patient scatter measurements, a CTDI Phantom head phantom was located centrally in the Ceretom™ bore. Body attenuation was obtained by means of a chest phantom (actually an inverted and rotated pelvic phantom) located near the proximity of the chest. The shadow shields were located parallel to the scanner's z-axis as shown in figure 2(a); this should be the worse case scenario where a radiographer cannot close these scatter shields further in order to be able to observe the patient. It should be noted however, that the more usual location of the shadow shields during a patient acquisition should be as shown in figure 2(b).

A matrix of markers were placed 0.5 m apart to 2 m from the iso-centre and 1 m apart further out, centred on the iso-centre to form an 8 m × 8 m matrix around the unit. Because the ward was too small, it was not possible to extend measurements 8 m in all directions. Instead, measurements were made of one quadrant, then the Ceretom™ was rotated by 180° so that the opposite quadrant could be measured, consequently, mirror symmetry parallel to the z-axis has been assumed in all scatter measurements.

A Radcal 9010 dosimeter with associated 1800 cm³ ionisation chamber, was used to take each measurement at two different heights above the floor level; (the centre of the unit's bore (97 cm), and 80 cm above the iso-centre; 177 cm), out to a distance of 4 m from the iso-centre. This was done to try to obtain some estimate of the local scatter direction and possibly detect hot spots. As there was less variation with height than with the distance from the iso-centre, the iso-centre measurements were used for subsequent calculations.

The dose rates were measured using a 120 kV, 7 mA, 6 s acquisition; the maximum tube rating. The normal acquisition is 4 revolutions per slice at 1 s per revolution giving 4 s per slice, i.e. using a 1 cm slice width will take 100 s assuming a 25 cm acquisition length. The measured doses were corrected using a cross-calibration, obtained from an ionisation chamber calibrated by the Radiation Protection Centre at St George's Healthcare NHS Trust [10], and traceable to the NPL standard, and converted to dose rate/mAs, allowing the scatter dose to be calculated for any particular scan parameters.

The new scatter map was used to designate the controlled area according to the guidance given in appendix 11 of the MDGN. These results are also shown in figure 3(b) and were based on a maximum of 5 acquisitions per day, 7 days per week. For comparison, figure 3(a) gives the same map generated from data obtained using the CTDI head phantom only, i.e. with no body attenuation. It is interesting to note that the presence of the body phantom increases scatter laterally while decreasing scatter towards the foot of the bed due to attenuation by the body. It was decided that the scatter map that included body attenuation would be used to define the designated areas as this represented the actual situation in the ward.

The ICU has a bed spacing of 4 m, so it was convenient to use the existing ward furniture to delineate the controlled area. This would satisfy regulations 16 and 18 as the physical bed could act as a simple delineation marker and simultaneously minimise the chance of accidental entrance to the controlled area during an acquisition. Although the main nurses' workstation lies in the centre of the ward, and outside of the controlled area, the radiographer would have to be located inside the controlled area to observe the patient. Consequently, it was decided to place a mobile screen at the foot of the bed of the patient having the acquisition to ensure the exposure to the radiographer is ALARP. The radiographer would then be able to acquire the image with adequate protection, simultaneously shield the nurses' workstation, and still be able to observe the patient. Thus, both adjacent patients and staff lie outside the controlled area.

The actual annual dose is dependant on the workload. Doses were then further restricted by limiting the use of the Ceretom™ to an allowed number of annual acquisitions. The area

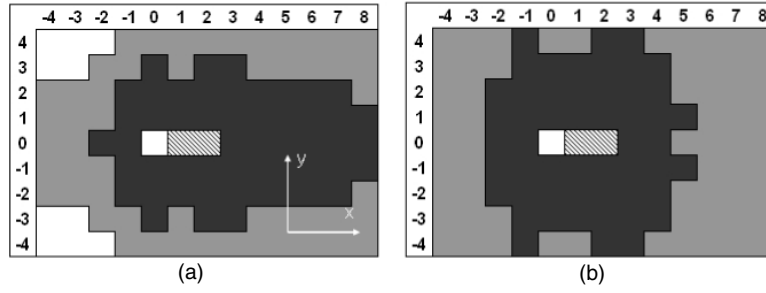


Figure 3. Figures showing the extent of the controlled and supervised areas around the unit. Controlled and supervised areas are represented by dark and light grey shaded areas respectively, the middle three squares represent the Ceretom™, (single white shaded area located at the origin), and couch, (the hatched area). Each square is 1 m². (a) Data using the CDTI head phantom only. (b) Data using the CTDI head and ‘chest’ phantom.

of the ward simulated was 15 m × 20 m area with bed spacings similar to that of the actual ward. Consequently, it was necessary to extend our scatter data beyond the distances we had physically measured. This was completed by fitting a 6th order polynomial to the dose data with an $R^2 \geq 0.998$ up to 10 m distance from the iso-centre to ensure agreement with experimental data, and assuming an inverse square relationship beyond that.

A 1 m × 1 m resolution coordinate system was then overlaid over the entire scatter data giving the dose at each point as $D(x, y)$ with the point $D(0, 0)$ centred on the CT unit itself as shown in figure 3(b). The ward was also given a coordinate system of similar resolution but the origin is located as shown in figure 4; each point being designated $P(x', y')$. Therefore, the accumulated dose at each point in the ward depends on the value of the scattered dose relative to the Ceretom™ at the time, and the total accumulated dose can be calculated at each point in the ward using:

$$D(x', y') = \sum_{n=1}^N D(m, n) \quad (1)$$

where

$$m = (-1)^{n+1} x' - x \quad (2)$$

determines the x ordinate and

$$n = (-1)^{n+1} y' - y \quad (3)$$

determines the y ordinate. n is the bed number as given in figure 4, for a maximum of $N = 8$ beds, using the ward, (x', y') , and scatter map, (x, y) coordinate systems. The value $(-1)^{n+1}$ accounts for the necessity to invert the data for odd numbered beds because the Ceretom™ faces the opposite direction during these acquisitions. In this manner it is possible to obtain the total accumulated annual dose in each part of the ward as shown in figure 4.

This data was then modified to calculate the likely dose to the adjacent patients as follows: the maximum patient stay in ICU is 60 days [11]. Therefore, the worst case scenario is when the patient is surrounded by other patients undergoing CT acquisitions. Figure 4 shows that for an equal number of acquisitions per bed, bed 6 incurs the greatest dose. Therefore, one can then use a planning constraint to calculate the maximum number of annual acquisitions per bed allowed before the scatter doses exceed the planning dose constraint, (in this case, the adjacent patient is considered a member of the public). A dose planning constraint of 150 μGy was used to account for all sources such as ward radiography and ensure no patient is exposed to

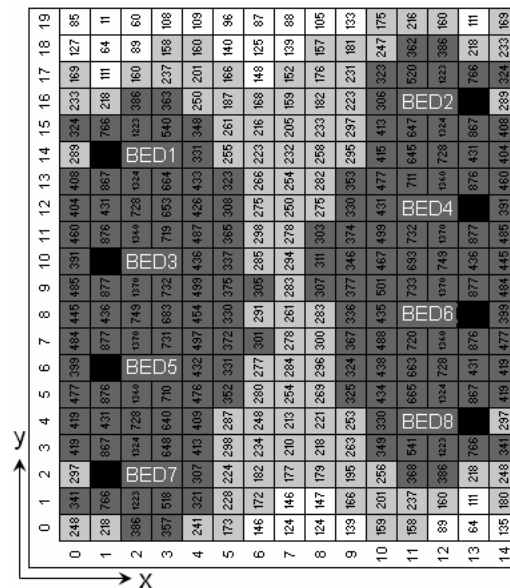


Figure 4. Figure showing the accumulated dose in μGy in the simulated ward based on 105 acquisitions per bed per year. Bed spacing is 4 m apart. The increasing shades of grey denote accumulated dose of less than $150 \mu\text{Gy}$, $150\text{--}300 \mu\text{Gy}$ and greater than $300 \mu\text{Gy}$ respectively.

the more usual $300 \mu\text{Sv}$ in any one year. To calculate the patient dose, one simply calculates the accumulated dose due to all other beds around bed 6 ensuring bed 6 itself contributes nothing to the calculation.

As may be expected the central beds in the ward accrue the highest accumulated doses due to the contribution from acquisitions in outlying beds. The limiting number of annual acquisitions per bed occurred in bed 6 with a total maximum number of acquisitions per bed per year of 290. This accumulates a maximum dose near bed 6 of $147 \mu\text{Gy}$, (see the dashed area in figure 5(a)).

A similar method may be used to examine the staff dose for ward nurses. Similarly to adjacent patients, ward nurses were not considered radiation workers, and therefore, a planning dose constraint of $150 \mu\text{Gy}$ was again applied. However, although these members of staff are usually a considerable distance from any acquisition, they can spend a significant amount of their working day at, or near the nurses workstation located in the centre of the ward, and marked as the area encompassing the dashed line in figure 5(b). Therefore it was decided to apply the $150 \mu\text{Gy}$ planning dose constraint to the middle 3 m of the ward and assume staff members spend 100% of their time in this area as a worst case scenario. Because the workstation is roughly equidistant to each bed, the accumulated dose limits the maximum number of acquisitions per bed per year substantially to no more than 65. Staff were assumed to work a 40 week year; the results being shown in figure 5(b).

In addition to the issues over engineering controls discussed in this paper, there were a number of other issues pertaining to general health and safety concerns of the use of the CeretomTM to staff. Of these, the most significant were an inadequate audible alarm during exposure, and the possibility of trapping feet under the unit. As a number of other Trusts in the UK had shown interest in the CeretomTM, it was thought appropriate to consult HSE.

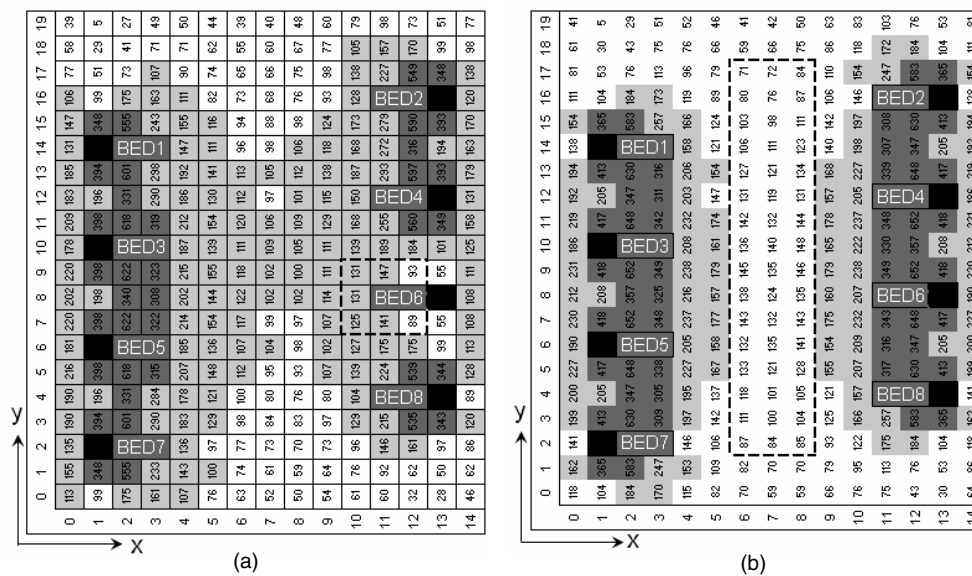


Figure 5. Figures showing the annual accumulated dose for a adjacent patients and staff. All accumulated doses are quoted in μGy . (a) Figure showing the accumulated dose for a patient staying in bed 6 for a maximum of 60 days, based on 290 acquisitions per bed per year. (b) Figure showing the accumulated dose around the ward for staff working 40 weeks per year, based on 65 acquisitions per bed per year.

Discussions with the manufacturer, UK distributor and HSE resulted in a modification to the CeretomTM; an audible alarm was fitted and labels were attached to the unit warning of its weight and trapping hazard. Discussions with HSE over ACOP paragraph 79 centred around the premise that the CeretomTM was bought to image patients who were critically ill and that it would be potentially life threatening to move them. Therefore, if it was life threatening to send them to a fixed facility, and the clinical justification was documented in patient notes; only then would use of the CeretomTM be justified in an open ward. In addition, because the CeretomTM is considered an emergency piece of equipment, the logical extension to the justification of use is that patients must have access to the CeretomTM 24 h a day, 7 days a week. Thus the service would have to be available at all times. In addition, the local rules were extended to ensure the radiographer performing the acquisition wore a 0.35 mm lead equivalent apron. This was because in the event of an emergency, and the failure of the wireless connection between laptop and CT unit, the only emergency off button is on the CeretomTM.

3. Conclusion

Even with the proposed restrictions of use resulting from the discussions with the HSE, the use of the CeretomTM in an open ward relies on the large bed spacing, extra shielding and a restriction on the number of annual acquisitions per bed. Therefore, with a 4 m bed separation, a maximum of 65 acquisitions per bed per year could be permitted whilst adhering to the planning dose constraint of a 0.3 mSv dose to the public. It is interesting but not surprising that it is the staff dose and not the patient dose that is the limiting factor in the number of acquisitions that can be permitted in any one year. In addition, although it is not strictly necessary to designate the area out to each adjacent bed a controlled area, it was convenient from the viewpoint of

ensuring the controlled area was delineated. Finally, because the ICU has already been built to include numerous pieces of ancillary equipment attached to the ceiling near the head of each bed, the ancillary equipment surrounding each bed makes it difficult to enter the controlled area from anywhere except at the foot of the bed nearest the radiographer performing the acquisition.

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