SHORT COMMUNICATION

Scatter radiation intensities around full-field digital mammography units

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ABSTRACT. The aim of this study was to investigate the scatter radiation intensity around digital mammography systems and apply these data to standard shielding calculations to reveal whether shielding design of existing breast screening rooms is adequate for the use of digital mammography systems. Three digital mammography systems from GE Healthcare, Hologic and Philips were employed in the study. A breast-equivalent phantom was imaged under clinical workload conditions and scatter radiation intensities around the digital mammography systems were measured for a range of angles in three planes using an ionisation chamber. The results were compared with those from previous studies of film-screen systems. It may be deduced from the results that scattering in the backward direction is significant for all three systems, while scattering in the forward direction can be significant for some planes around the GE and Hologic systems. Measurements at typical clinical settings on each system revealed the Philips system to have markedly lower scatter radiation intensities than the other systems. Substituting the measured scattered radiation intensity into shielding calculations yielded barrier requirements similar to those already in place at the screening centres operating these systems. Current radiation protection requirements based on film-screen technology remain sufficient when applied to rooms with digital mammography installations and no alteration is required to the structural shielding.

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BreastCheck, The Irish National Breast Screening Programme, was launched in 2000. The programme invites women ranging in age from 50 to 64 years to undergo breast cancer screening every 2 years. Screening is performed both onsite in static screening clinics and offsite in mobile units. The transition to digital mammography occurred on a phased basis following its initial introduction in 2005. Between April 2005 and December 2007, 18.6% of clients (35 204 of 188 823) were screened on digital systems. In April 2008, BreastCheck became the first national screening programme in Europe to become fully digital [1].

The transition to full field digital mammography (FFDM) imaging in recent years has seen a shift to harder X-ray spectra through the use of novel anode targets such as rhodium (Rh) and tungsten (W) in combination with filters such as Rh, silver (Ag) and aluminium (Al), operating at higher peak tube potential (kVp) values. Analogue film-screen mammography was typically performed using spectral exposure factors lower than 30 kVp for a molybdenum/molybdenum (Mo/Mo) anode/filter combination.

While this transition to digital mammography has taken place, most of the current literature investigating the radiation protection requirements for mammography

installations is based on scatter intensities acquired for Mo/Mo systems and using a small image field size (18×24 cm).

For all modern mammography units, the primary beam is intercepted by the image receptor assembly. European [2] and US [3] guidelines permit only a very narrow strip of the primary beam to overlap the image receptor assembly along the chest wall edge of the beam. This radiation is usually attenuated to insignificant levels by the patient and, consequently, only secondary radiation must be considered for radiation protection purposes in mammography rooms. Furthermore, it is reasonable to assume that radiation scattered by the patient is the dominant source of secondary radiation, given the minuscule leakage intensity observed at mammography accelerating potentials [4]. Therefore, gypsum wallboard and plate glass may provide adequate protection if the boundary is at sufficient distance. Wooden doors usually incorporate additional shielding owing to the impractical thicknesses that are often computed from shielding calculations while lead acrylic or lead glass is incorporated into the operator's console.

The methods published in the British Institute of Radiology shielding report [5] were utilised for all the shielding calculations in this study. In this method, the thickness of material required to provide the desired transmission is calculated using an empirical model developed by Archer et al [6]:

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$$\chi = \frac{1}{\alpha\gamma} \ln \left[\frac{B^{-\gamma} + \left(\frac{\beta}{\alpha}\right)}{1 + \left(\frac{\beta}{\alpha}\right)} \right] \quad (1)$$

where χ is the thickness of material, B is the broad beam transmission factor and α , β and γ are fitting parameters which depend on the material and operating potential. The broad beam transmission factor, B , is given by

$$B = \frac{D_C}{AIS \times T} \quad (2)$$

where D_C is a dose constraint, AIS is the annual incident scatter and T is the occupancy factor.

The aim of this study was to investigate scatter radiation intensity around modern digital mammography systems by imaging a breast equivalent phantom under clinical conditions. Furthermore, these scatter measurements were substituted into a shielding calculation and results compared with current shielding design criteria to determine whether additional radiation protection or alteration to present shielding was required.

Materials and methods

Scatter radiation was studied on three FFDM systems: General Electric Essential (GE Medical Systems, Buc, France), Hologic Selenia (Hologic, Bedford, MA) and Philips MDM (Philips, Solna, Sweden). Each system

Figure 1. Illustration of the experimental set-up used in the measurements of the scattered radiation.

differs with regard to the anode/filter combinations used as well as detector technology and operation of the automatic exposure control (AEC) system.

The GE system has a dual-track anode composed of Mo and Rh targets in combination with Mo or Rh filters. The GE Essential has an indirect conversion detector which consists of a flat-panel amorphous silicon diode array with a caesium iodide (CsI) needle structure scintillator. The GE Essential uses a feature called automatic optimisation of parameters (AOP) to optimise image quality under certain constraints and technical limitations. There are three fully automated exposure modes available on the Essential: Dose, Contrast and Standard. The systems working in BreastCheck are all set to operate in the Standard mode, which involves the automatic selection of anode/filter, kilovoltage and tube current-time product [7]. At the time of testing, all GE units were set up using the Classic version of the AOP tables.

The Hologic Selenia system is equipped with a W anode and a choice of Rh or Ag filtration. The detector used is a flat-panel amorphous-selenium detector, which

Figure 2. Illustration of the three planes (a, b, c) in which scatter radiation was measured at various angles. The planes a, b, c represent the planes 30° towards the nipple edge of the phantom, parallel to the chest wall edge of the phantom, 30° towards the chest wall edge of the phantom, respectively.

performs a direct conversion of X-rays to a digital signal. It consists of a 200- μm layer of amorphous selenium bonded to a thin-film transistor (TFT) array. This system has four modes of AEC: Auto-filter, Auto-kV, Auto-time and thickness equivalent control (TEC), and four distinct pre-set dose levels. Systems working at BreastCheck were all set to operate in the Auto-filter mode (control of exposure duration and optimum selection of kilovoltage and filter) and the standard screening dose setting [7].

The Philips MDM is a multiple slit scanning photon counting system with a W/Al anode/filter combination. This system uses the compressed breast thickness to set the kilovoltage and the initial scan speed to select a specific exposure. It then uses a form of exposure control

called *SmartAEC*TM (Philips), which continuously adjusts the exposure and optimises the dose level to the local density of the breast throughout the scan [7].

For the purpose of this study, the three FFDM systems were operated in manual mode, which allowed selection of kilovoltage, tube current–time product and anode/filter combination. All three systems were subject to routine medical physics quality assurance during the period of this study in accordance with the recommendations of the European Guidelines for Quality Assurance in Breast Cancer Screening and Diagnosis [2] and were found to conform to the standards.

Scatter dose measurements were made with a Radcal Model 10X6-6M ionisation chamber (Radcal Corporation,

Figure 3. Scatter dose distributions measured at 1 m from the phantom around the GE Essential system (GE Medical Systems, Buc, France), for various anode/filter combinations, peak kilovoltage and tube current–time product values in the planes (a) 30° towards the nipple edge of the phantom, (b) parallel to the chest wall edge of the phantom and (c) 30° towards the chest wall edge of the phantom. Mo, molybdenum; Rh, rhodium.

Monrovia, CA). This dedicated mammography chamber has a chamber volume of 6 cm^3 . It is used extensively for mammography measurements because of its flat energy response in the mammographic energy range (10–40 keV) and its applicability for any mammographic tube track-filter combination. It has a minimum dose limit of $0.1\text{ }\mu\text{Gy}$, and is constructed of a 0.7 mg cm^{-2} metalised polyester window and a polyacetal exterior. Its calibration accuracy is $\pm 4\%$ using X-rays at 20 kVp and 0.26 mm Al half-value layer. This chamber was connected via an ionisation chamber digitiser, Model 9660, to a Radcal ACCU-PRO control unit, Model 9096 (Radcal Corporation), which gave automatic readings of dose-in-air. Both the Radcal ACCU-PRO control unit and the

ionisation chamber had been calibrated in terms of absorbed dose-in-air, and tested by the manufacturer in the 6 months prior to the measurement period. This calibration is traceable to the American National Institute of Standards and Technology.

A Computerized Image Reference System 6 cm 20% glandular/80% adipose composition breast phantom was used to mimic the breast and create scatter radiation (Computerized Imaging Reference Systems, Norfolk, VA). This is a tissue-equivalent phantom designed specifically to test the performance of mammographic systems. It is realistically shaped and has similar tissue equivalency to a typical breast. This phantom was chosen for several reasons: (i) it represents the average breast thickness

Figure 4. Scatter dose distributions measured at 1 m from the phantom around the Hologic Selenia system (Hologic, Bedford, MA) for various anode/filter combinations, peak kilovoltage and tube current–time product values in the planes (a) 30° towards the nipple edge of the phantom, (b) parallel to the chest wall edge of the phantom and (c) 30° towards the chest wall edge of the phantom. Ag, silver; Rh, rhodium; W, tungsten.

measured in successive dose surveys in this screening programme [7], (ii) the larger percentage of adipose tissue represents a worst case scenario because adipose tissue produces more backscatter than glandular tissue and (iii) this phantom thickness is sufficient to produce close to 100% of the maximum backscatter fraction [8].

Scatter radiation was measured at a distance of 1 m from the centre of the phantom for various angles ranging from 0° to 165°. Beyond this angle the tube housing intercepts the backscatter from the phantom. Figure 1 shows the experimental arrangement used to measure the scatter radiation intensity at a distance of 1 m.

Measurement of the scatter radiation intensity at different angles was achieved by tilting the mammography

unit and matching the height of the centre of the chamber to the centre of the phantom, a method previously used by Simpkin [4]. For all measurements, the thin polyester window of the chamber was orientated to face the phantom because it has a directional response. Measurements were made for smaller angle increments around the angle of maximum scatter and where any peaks occurred in the dose readings. Scatter measurements were made in three planes around each unit, as illustrated in Figure 2. One was parallel to the chest wall edge of the phantom while the other two were 30° either side of this plane (towards the nipple and chest wall edges of the phantom). For all scatter measurements, the compression paddle was used to compress the phantom with a standard force of 100 N.

Figure 5. Scatter dose distributions measured at 1 m from the phantom around the Philips system (MDM, Philips, Solna, Sweden), for various anode/filter combinations, peak kilovoltage and tube current–time product values in the planes (a) 30° towards the nipple edge of the phantom, (b) parallel to the chest wall edge of the phantom and (c) 30° towards the chest wall edge of the phantom. Al, aluminium; W, tungsten.

Exposures were made for every possible anode/filter combination. Typical peak kilovoltage values within the clinically used range were chosen by reference to recent data from a dose survey carried out within BreastCheck [9]. The peak kilovoltage values chosen were those selected automatically by the mammography unit for the actual breast thickness used. A higher tube current-time product (mAs) value than was clinically recorded was also chosen (100 mAs for the GE and Hologic, and 13.5 mAs for the Philips system) to ensure adequate detection statistics for scatter radiation at a 1-m distance from the phantom. This resulted in some potential overestimation of scatter radiation which was considered prudent for operational radiation protection measurements.

Field sizes of 19×23, 18×24 and 24×26 cm were used on the GE, Hologic and Philips systems, respectively.

Results and discussion

Figures 3–5 show the scatter dose as a function of the scattering angle for the GE, Hologic and Philips systems, respectively. Each figure has three curves representing each of the planes outlined earlier in Figure 2: 30° towards the nipple edge of the phantom, parallel to the chest wall edge of the phantom and 30° towards the chest wall edge of the phantom.

It is evident from Figures 3–5 that scatter dose distributions were system specific. On the GE Essential, scattering in the backward direction dominated with comparatively little scatter in the forward direction, except for the plane parallel to the chest wall edge of the phantom, where a sharp increase was seen in the measured scatter dose at approximately 30°. For angles >90°, a similar trend was observed for the Hologic Selenia system. However, for angles <90°, a broad dominant peak was seen in the planes parallel to the chest wall edge of the phantom and 30° towards the nipple edge of the phantom. This began at around 60° and built up to a peak at approximately 30°. Below 30°, scatter decreased very sharply. At 28 kVp, this peak was equivalent in magnitude to the maximum backscattering intensity measured, while for 30 kVp it was greater. The dose distributions for the Philips system did not display a peak of this kind. In fact, below 60°, no scattered radiation was detected. Hence, backscattered radiation dominated on this system.

For very small angles where the detector was effectively under the image receptor assembly, the scatter readings were nil for all systems and in all planes except for the plane 30° towards the chest wall edge of the phantom. In this plane, the image receptor assembly does not extend forward enough to intercept X-rays scattered through small angles. The nil values in the other planes proved that the image receptor assembly was effective at intercepting the primary beam. On all systems, the intensity of backscattered radiation began to fall off sharply beyond 165° owing to interception of the X-rays by the tube housing. Again, this did not occur in the plane 30° towards the chest wall edge of the phantom because the tube housing did not protrude far beyond the chest wall edge of the image receptor assembly.

The peaks observed in the GE and Hologic data have been noted and commented on by Simeoni and Thiele [10] and Simpkin [4], respectively. Simpkin postulated that a

peak in scattered radiation around this angle may be due to scatter in the X-ray tube housing and collimator. The sudden disappearance of this peak when the chamber moved to an angle which allows the image-receptor assembly to block the line of sight between the chamber and the collimator/tube housing assembly suggests that the source of this scattered radiation is not from the phantom or image-receptor, rather further away, close to the source of the primary beam. In the Hologic data, this peak appeared to increase in dominance as the peak kilovoltage was increased from 28 to 30 kVp. A spot check at the system maximum potential, 39 kVp, confirmed this increased dominance with this peak becoming almost double the maximum backscattered intensity measured for clinical simulations. The absence of a peak of this kind in the Philips data is most likely owing to its unique style of close collimation, where a highly collimated thin fan beam of X-rays are scanned across the breast.

The maximum scatter dose measured on the GE, Hologic and Philips systems at a 1-m distance were 6.2 µGy, 4.5 µGy and 1.5 µGy, respectively.

The shape of the scatter dose distribution varied considerably across all three systems. The curves in Figure 6 give an indication of this variation for the plane parallel to the chest wall edge of the phantom. This is a fixed distance scatter plot (1 m) and is not to scale to aid interpretation of the curves.

Using the maximum scattered dose recorded for each system and multiplying it by 40 000 (40 patients per day, 4 exposures per patient, 5 days per week, 50 weeks per

Figure 6. Fixed distance (1 m) scatter plot of the shape of the scattered radiation profiles around a patient for each digital mammography system in the plane parallel to the chest wall edge of the phantom.

Table 1. Secondary barrier requirements 1 m from a digital mammography unit used under typical conditions

Digital mammography system	GE Essential ^a	Hologic Selenia ^a	Philips MDM ^a
Maximum scatter dose at 1 m (μ Gy)	6.2	4.5	1.5
Maximum annual Incident Scatter (mGy)	248	180	60
Dose constraint for a member of the public (mGy)	0.3	0.3	0.3
Occupancy	1	1	1
Broad beam transmission factor	1.21×10^{-3}	1.67×10^{-3}	5.00×10^{-3}
Gypsum plasterboard thickness (mm)	21	19	18
Plate glass thickness (mm)	9	8	8
Wood thickness (mm)	180	169	157

^aGE Essential manufactured by GE Medical Systems, Buc, France; Hologic Selenia by Hologic, Bedford, MA; and Philips MDM by Philips, Solna, Sweden.

year) provided an estimate of the AIS for typical clinical use. Substituting these values into Equation (2) allowed calculation of the broad beam transmission factor, which in turn allowed calculation of the barrier thickness required at a 1-m distance for the construction materials commonly used for shielding mammography screening rooms. These results are summarised in Table 1. An advisory design dose constraint D_C of 0.3 mSv per year effective dose for radiation protection planning [14] was used in these calculations. However, the measurements made of scatter dose will represent a significant overestimate of effective dose owing to varying distribution of photon fluence and self-shielding for the energy range used in mammography [5]. The fitting parameters used in these calculations were extracted from the Simpkin data [11]. These values are for a Mo anode with Mo filtration and were used for calculations on all three systems because of the unavailability of data for Rh and W. In any case, differences in the shielding requirements between mammography beams generated by Mo, Rh or W anodes with Mo, Rh and Al filtration at operating potentials not exceeding 35 kVp were not considered significant [12].

Conclusions

For radiation protection purposes, it is important to ensure that the shielding provided by the walls, ceiling and floor of an X-ray room are adequate. Shielding must be sufficient to maintain radiation dose to staff and patients in adjoining areas below the regulatory limits [13]. Accurate assessment of the scatter radiation intensities is essential for calculating the shielding requirements for any X-ray installation.

This study has shown how scattered radiation dose varies with scattering angle and scattering plane for three FFDM systems. Each system was found to have its own unique scatter profile. The results have indicated that the current use of regular building materials provides adequate shielding for FFDM units, using new target/filter combinations and operating at higher peak kilovoltage. BIR 2000 recommends using 24 mm of Gypsum plasterboard, 10 mm of glass and 196 mm of wood in mammography rooms at 1 m (assuming 100 mAs, 30–35 kV, Mo/Mo). None of these values were exceeded even when the maximum scatter intensity recorded was used [5].

Considering that many of the room boundaries in this study are at a distance >1 m, these shielding

requirements will overestimate the necessary shielding. Owing to the impracticable thicknesses of wood required, even at a 2-m distance, the use of additional shielding material such as steel or lead in mammography room doors is still required.

Although current shielding reports for diagnostic X-ray rooms quote the greatest scatter at $\sim 160^\circ$, this study has shown that scatter in the forward direction for some units can be significant. For the Hologic system in particular, equally high scatter intensities were found at $\sim 30^\circ$ for clinically used peak kilovoltage, while it was approximately double at the system maximum peak kilovoltage. Regardless of the cause of this scatter distribution at these angles, it is evident that scatter in the forward direction must not be ignored for mammography shielding calculations.

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