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QUALITY CONTROL IN MAMMARY RADIOGRAPHY

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The doses and image qualities produced by equipment for mammary radiography have been the subject of much interest throughout the world. This is due to the fact that the skin doses are usually much higher than in other types of radiographic examinations and because of fears that the risk of breast malignancy induced by the high doses exceeds the benefit derived from the examination. In some cases the doses received by the patients may be unduly high as a result of the many different combinations of equipment, image recording techniques and processors currently in use. Furthermore, the information contained in the image may in some cases be insufficient, resulting in unnecessary re-exposures or progress of a disease to the fatal stage before detection.

The skin doses reported in the literature are mostly between 0.04 and 500 mGy per exposure (BICEHOUSE 1975, JANS 1976, WATSON 1977, JOHN et coll. 1978), though in some cases doses have been as high as several Gy (WRIGHT et coll. 1971).

The quality of the images can be evaluated in several different ways. It depends essentially on the film density, which may be 0.3 to 4 optical densities (STANTON et coll. 1963, HAUS et coll. 1977, SÄBEL et coll. 1977, ARNOLD et coll. 1978, HAGEMANN et coll. 1978, FRIEDRICH & WESKAMP 1979). The image quality can be analysed in terms of contrast, which can be evaluated by a variety of methods (STANTON et coll. 1963, RICCI et coll. 1974, EVANS et coll. 1975, BERNSTEIN et coll. 1977, SICKLES et coll. 1977), and resolution, which can be determined either visually or by means of a modulation transfer function (MTF). Depending on how it is determined, the resolution obtained may be 1.2 to >20 lp/mm (HAUS et coll. 1977, SICKLES et coll., SÄBEL et coll., WILSON 1977, ARNOLD et coll., HAGEMANN et coll., FRIEDRICH & WESKAMP). Attempts have also been made to evaluate the image quality by subjectively examining films of either patients or phantoms (KARLSSON et coll. 1976, TONGE et coll. 1976, HAUS et coll. 1977, SICKLES et coll., SPENCER et coll. 1977, WATSON, PATEROK et coll. 1978, EGAN et coll. 1979, FRIEDRICH & WESKAMP, STANTON et coll. 1979).

During the summer of 1978 this Institute carried out an inspection of all equipments being used in Finland for mammary radiography. The aim was to determine patient doses, image qualities, and the conditions affecting these factors.

Material and Methods

In 1978, 29 equipments were used in Finland for mammary radiography, 14 being specially made and with special roentgen tubes (Mo anode and Mo with or without Al filter). The other 15 equipments had ordinary diagnostic tubes (W or Re-W anode and Al or Mo filter) and had been adapted to varying degrees for mammary radiography. Thirty-five different imaging methods were in use. Non-screen films were still in use at 10 centres, xerography at one centre, and ordinary cassette-film combinations at 2 centres. The rest were Agfa-Gevaert, Du Pont and Kodak screen (vacuum)-film combinations.

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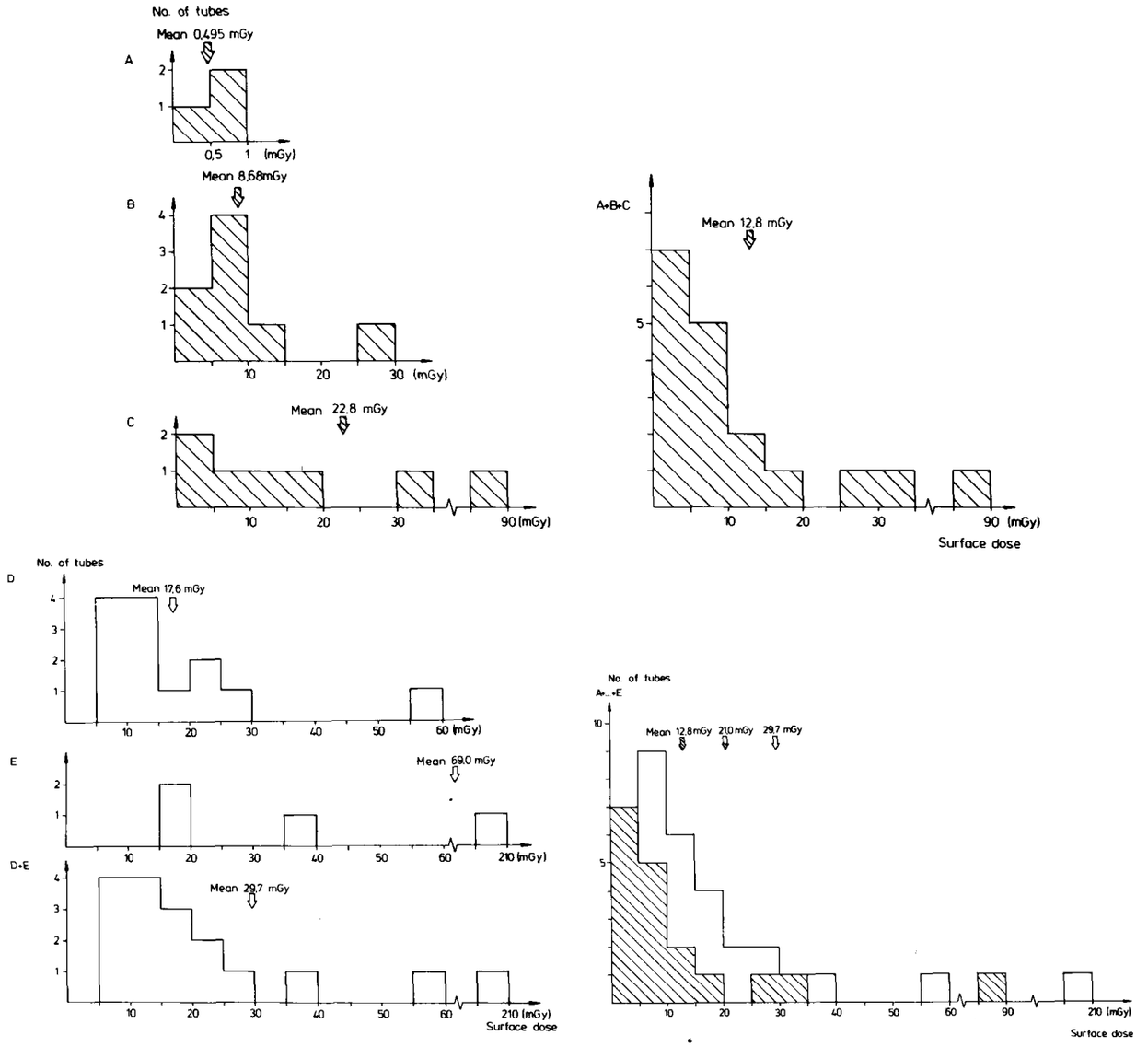

Fig. 1. Distribution of surface doses (6 cm phantom). □ special tube (17). ▨ ordinary tube (18). A: Ordinary tube, ordinary cassette and film. B: Ordinary tube, vacuum cassette and special film. C: Ordinary tube, non-screen film and xeroradiography. D: Special tube (Mo/Mo, Mo/Al), vacuum cassette and special film. E: Special tube (Mo/Mo, Mo/Al), non-screen film.

At all the centres, images of 2, 4 and 6 cm thick D-shaped polythene phantoms were produced (cranio-caudal projection) either manually or using a phototimer based on the pre-set values (kV, mA and s or mAs), exposure geometries and image recording systems used. The phantoms had diameters of 11 and 16 cm. In order to determine the image quality, i.e. the contrast and resolution, a step wedge and a resolution plate were placed on the surface of the phantoms in the sternum-nipple direction and perpendicular to this direction. The step wedge had seven 0.09 mm thick Al steps. The resolution plates were type 0.7–521 with 2 to 10 lp/mm (thickness 0.05 mm Pb, supplied by Nuclear Associates, Carle Place, N.Y.), and type 53 with 0.25 to 10 lp/mm (0.05 mm Pb, supplied by Optik-Foto-Funk, Erlangen, Germany).

The photographic density of the films was measured with a Macbeth TD 502 densitometer. The mean of three measurements—the density in the sternum-nipple direction at a distance of 1 cm from the edges of the phantom and the density in the

Table 1

Mean values (calculated according to the number of tubes) and ranges for measurements made on ordinary, special and all tubes (6 cm phantom)

Parameter	Roentgen tubes					
	Ordinary		Special		All	
	Mean	Range	Mean	Range	Mean	Range
Exit dose (mGy)	1.75	0.0106–5.91	1.36	0.216–9.63	1.55	0.0106–9.63
Tube voltage (kV)	36	26–48	28	22–38	32	22–48
Tube current (mA)	236	80–450	144	25–250	208	25–450
Exposure time (s)	1.57	0.08–5.37	1.20	0.02–4.00	1.39	0.02–5.37
Charge (mAs)	242	32–859	110	49–258	236	32–859
Total filtration (mm Al)	2.56	0.78–13	0.57	0.50–0.67	1.60	0.50–13
First HVT (mm Al)	1.21	0.42–3.14	0.34	0.28–0.39	0.78	0.28–3.14
Homogeneity factor	0.45	0.35–0.52	0.44	0.37–0.44	0.45	0.35–0.52
Focus-film distance (cm)	79	50–113	48	29–70	64	29–113
Visual resolution using ×8 magnifying glass (lp/mm)	5.47	1.50–10	6.93	2.50–10	6.15	1.50–10
Focus size (mm)						
Longitudinal	1.42	0.92–2.24	1.06	0.28–1.72	1.24	0.28–2.24
Transverse	1.30	0.57–1.91	0.94	0.67–1.31	1.12	0.57–1.91

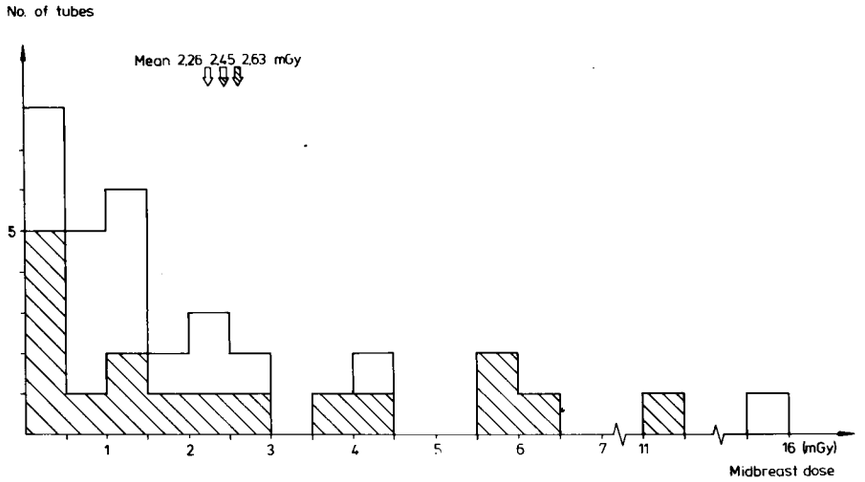

Fig. 2. Distribution of midbreast dose/single view of 6 cm thick breast. □ special tube (17). ▨ ordinary tube (17).

centre of the phantom—was taken as the mean gross density of the film. The density was measured at the centre of the steps and adjacent to the steps, to determine the contrast, which was calculated using the equation $C=\Delta B/B$, where ΔB is the difference between the density at the step and adjacent to the step and B is the density adjacent to the step.

The resolutions of the images were determined using a viewbox and visually without the use of a magnifying glass, and using a ×8 magnifying glass. The mean values obtained by three independent observers were taken for the resolutions.

Two 1015C monitors (MDH dosimeters) were employed for measurement of the primary exposures (exposures on the surfaces of the phantoms and exit exposures) and exposure times. Both monitors were calibrated at the standard laboratory of the Institute of Radiation Protection.

The tube currents (mA) were measured using a Tektronix current probe with a current transformer.

The current probe and one monitor, which was used to measure the exposures on the surface of the phantom, were connected to an oscilloscope. The exposure and current waveforms were photographed from the display screen of the oscilloscope. The tube voltages (kV) were measured using a Wisconsin mammographic penetrameter test cassette.

The geometries used in the cranio-caudal view were employed to measure simultaneously the surface (entrance exposure including backscatter) and exit exposures (at the centre of the radiation beam) for 2, 4 and 6 cm thick phantoms using the relevant manually pre-set values for the phantoms. On equipments with phototimers (8) these were used for the measurements.

First and second half-value thicknesses were determined for all tubes using Al absorbers. Using the first HVT value the signals were corrected by means of ionization chamber energy-dependency curves to yield exposure in unit of R. A conversion factor (for muscle) 9.17 mGy/R (STORM & LIER 1972) was then used to convert the surface exposures into absorbed doses on the skin and the exit exposures into absorbed doses at the exit point of the breast. The first HVT was also used to determine total filtrations for the tubes, and the homogeneity factors were then calculated (first HVT/second HVT).

The homogeneity of the radiation beam (heel effect) was determined from a film exposed at the position of the cassette holder. The mAs setting was chosen so as to avoid exposure outside the straight linear part of the density curve of the film (non-screen Kodak PE 4006). The size of the tube foci was determined using a 2° star raster.

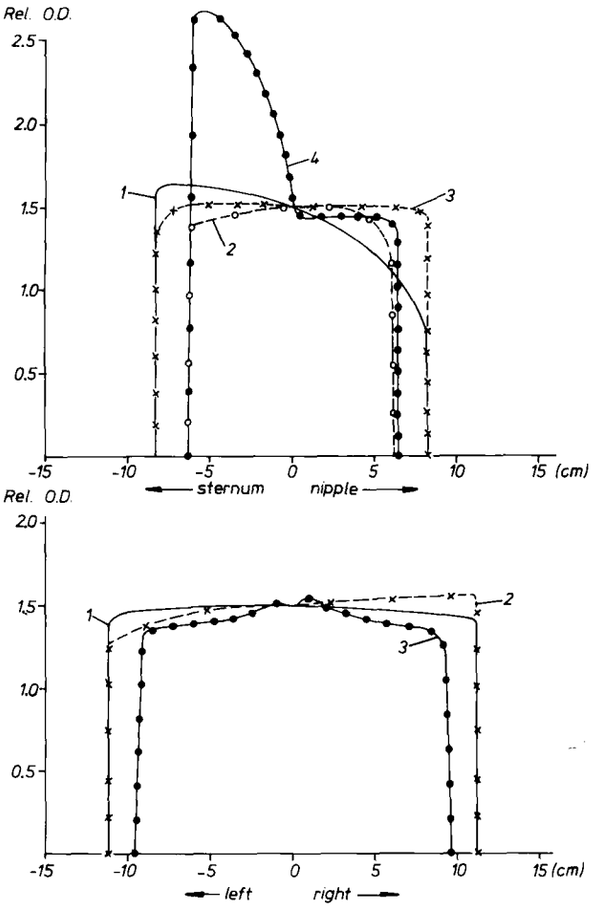

Fig. 3. Beam homogeneities produced by different tubes and by tubes placed in different positions.

		Anode angle	Projection
Top:	1	20°	← cathode 0 anode →
	2	12°	← anode 0 cathode →
	3	13°	Perpendicular to anode–cathode direction
	4	12°	← cathode 0 anode →
Bottom:	1	20°	Perpendicular to anode–cathode direction
	2	13°	← anode 0 cathode →
	3	12°	Perpendicular to anode–cathode direction

Results

The number of patients examined during 1978 was obtained from the records and reached a total of 11 090. The workload of the centres varied enormously, from 2 to 2 736 patients per year. The mean value was 382 patients per centre.

Because of the many differences between general purpose and special tubes the results are given separately for the imaging methods used: ordinary (18), special (17), and all tubes (35).

Patient dose. The distribution and mean values of surface doses obtained in cranio-caudal views of a 6 cm phantom for each of the various imaging methods used are given in Fig. 1. The mean values obtained for surface doses received from ordinary, special, and all tubes were 12.8, 9.7 and 21.0 mGy, respectively, with ranges of 44.7 μGy–86.2 mGy, 5.06–208 mGy, and 44.7 μGy–208 mGy. Thus, the highest dose (208 mGy) was almost 5 000 times higher than the lowest (44.7 μGy).

When special tubes were used the mean surface doses corresponding to all three phantom thicknesses were about twice those obtained with ordinary tubes. The surface doses obtained with the different imaging methods also differed clearly (Fig. 1). For

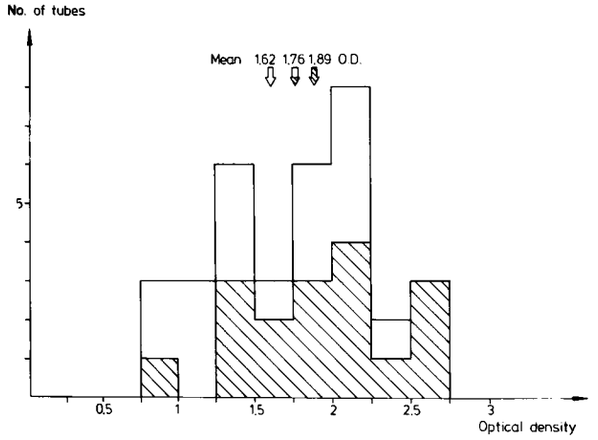

Fig. 4. Distribution of mean gross densities of the film (6 cm phantom). □ special tube (17). ▨ ordinary tube (17).

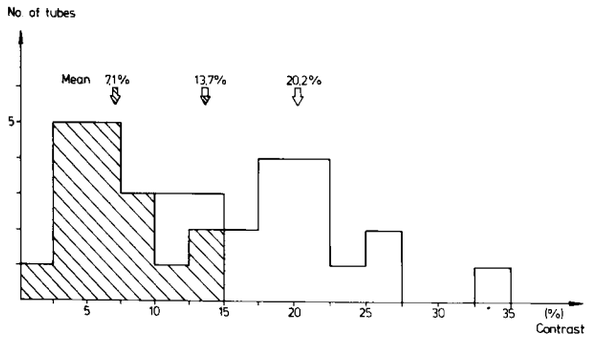

Fig. 5. Distribution of contrast levels (6 cm phantom). □ special tube (17). ▨ ordinary tube (17).

the individual equipment the surface dose by no means always increased exponentially as a function of the phantom thickness, sometimes increasing more rapidly and sometimes even remaining constant.

The mean values and ranges of the exit doses for the 6 cm phantom appear in Table 1. The highest dose was more than 900 times higher than the lowest, so that the dispersion of the exit doses was considerably smaller than that of the surface doses.

Only for a few equipments did the exit doses remain constant as the phantom thickness increased. The exit doses generally decreased as the phantom thickness increased, except in one case (measurement made on 19 equipments).

The absorbed dose to the breast is generally considered more important than the absorbed dose to the skin when evaluating the risk of radiation. Consequently, the absorbed doses were calculated using the values obtained for the 6 cm phantom. The mid-breast dose per view was calculated at the midpoint of a 6 cm thick breast (HAMMERSTEIN et coll. 1979). The distribution and mean values of the doses are shown in Fig. 2.

Factors affecting dose. The mean values and ranges of the measured tube voltages, tube currents, exposure times, charges (mAs), total filtration, first HV thicknesses, homogeneity factors and focus-film distances are given in Table 1.

The actual (measured) values for the voltage, current, exposure time and charge may have deviated from the pre-set values by ±27%, −50 to 448%, −25 to 115% and −50 to 500%, respectively. The measured values of the tube voltage usually increased linearly as the pre-set values increased. In 71 per cent of the 21 equipments measured, the actual tube current was lower than the pre-set value. Such a condition should not be accepted, since the exposure times can then be too long.

It should be pointed out that the total filtration in 12 of the ordinary tubes corresponded to more than 1 mm Al, a fact that indicates an inadequate optimization of the radiation energy.

In many cases a focus-film distance of 60 cm gave good image resolution in relation to the size of the focus. The focus-film distance was shorter than 60 cm in 18 equipments.

Examples of the homogeneity of the beams (heel effect) are given in Fig. 3. The beam may be extremely heterogeneous. The greatest change in density in the anode-cathode direction was 50 per cent.

The anode-cathode direction of the tubes was positioned in four different ways in relation to the sternum-nipple direction. The angles of inclination of the tubes were not measured. However, as Fig. 3 shows, the angles should be correctly adjusted in order to obtain maximum homogeneity of the beam.

Film density. The distribution and mean values of the mean gross density of the films are presented in Fig. 4 (6 cm phantom). The highest density (2.54 O.D.) was three times higher than the lowest (0.85 O.D.). Comparison of the densities obtained with screen-film combinations with those obtained with non-screen films gave mean values of 1.67 and 1.97 O.D., respectively, and ranges of 0.85 to 2.24 O.D. and 1.13 to 2.54 O.D.

The density of the films usually decreased as the phantom thickness increased, though in some cases it increased. Only in a few cases did the density remain the same. Very small differences were ob-

served in the optimization and stability of the film density (as a function of the phantom thickness) using phototimed and manual exposure.

Contrast. The appearance of the Al step wedge for phantoms of various thicknesses using ordinary and special roentgen tubes is given in Table 2. All the steps were always visible, with special tubes. When ordinary tubes were used, all the steps were visible in 32 of the 47 films. The fourth step was the first one visible (thickness 0.36 mm Al) in all images; therefore, the contrast levels were determined at the fourth step. The distribution and mean values of the contrast levels obtained from exposure of the 6 cm phantom appear in Fig. 5. The best equipment provided a contrast (33%) that was 22 times higher than that of the worst one (1.5%).

The contrast of the films usually diminished as the thickness of the phantom increased. However, in a few cases it increased, a fact that indicated that the imaging methods had not been optimized.

The most general reasons for the poorer contrast obtained with ordinary tubes compared with that produced by special tubes were the anode material (W and Re-W), the higher total filtration, and in some cases the higher tube tension. This appears more clearly in Fig. 6, which shows all contrasts obtained as a function of the first HVT (6 cm phantom).

The contrast increases as the first HVT diminishes; a tube with an Mo anode should be used if a high contrast is required (Fig. 6).

Resolution. The distribution and mean values of the resolution determined visually in the sternum-nipple direction are presented in Fig. 7. The differences in resolution produced by ordinary and special tubes were only around one lp/mm, and the resolution of the best equipment (8.7 lp/mm) was 6 times that of the poorest (1.5 lp/mm).

The results of the resolution determined visually for the 6 cm phantom using a ×8 magnifying glass (sternum-nipple direction) are given in Table 1. The resolution was generally around one lp/mm greater than those determined visually, and the resolution of the best equipment (10 lp/mm) was 7 times greater than that of the poorest (1.5 lp/mm).

For the individual equipment the resolution generally decreased as the thickness of the phantom increased. In the energy range of mammary radiography the first HVT (tube voltage and total filtration) had no effect on the resolution when the phantom thickness was kept constant. On the other hand, the resolution improved as the focus size decreased or the focus-film distance increased.

Table 2

Number of images corresponding to the smallest visible step thickness of an Al step wedge obtained during exposure of phantoms of various thicknesses using ordinary and special tubes. The number of images analysed is given in parentheses after the tube type

Tube	Phantom thickness (cm)	Number of images at different Al steps (mm)			
		0.09	0.18	0.27	0.36
Ordinary (18)	6	10	6	2	
Special (17)	6	17			
Ordinary (14)	4	12	1		1
Special (15)	4	15			
Ordinary (15)	2	10	1	2	2
Special (16)	2	16			

Table 3

Number of tubes corresponding to tube voltage and half-value thickness ranges. The outlined area is taken as the optimum energy range. Per cent in parentheses

Measured tube voltage (kV)	Measured first HVT/mm Al		
	<0.4	0.4–0.7	>0.7
<25	2 (6)		
25–35	14 (41)	7 (21)	
>35	1 (3)		10 (29)

Focus size. Means and ranges of the measured focus size in both the longitudinal and transverse directions are given in Table 1. Only one ordinary and two special tubes had a focus size falling within IEC 336 tolerance limits (IEC 1970). The focus size was in general larger than the upper tolerance limits, although 5 foci were smaller than the lower tolerance limits. Tubes from one particular manufacturer had a focus size well within the tolerance limits.

Optimization of radiation energy. In Table 3 are given the numbers and percentages of tubes corresponding to a certain tube potential and first HVT range at exposure of the 6 cm phantom. The table indicates that in 38 per cent of the films the radiation energy had not been optimized. The optimum energy and voltage ranges can be defined using the data

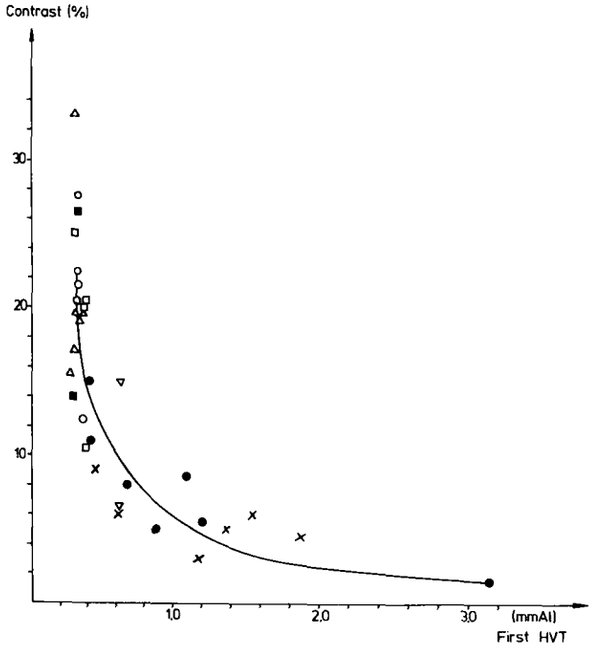

Fig. 6. Contrast as a function of first HVT (6 cm phantom). Different manufacturers of special tubes (■ ○ △ □). Different manufacturers of ordinary tubes (▽ ● ×).

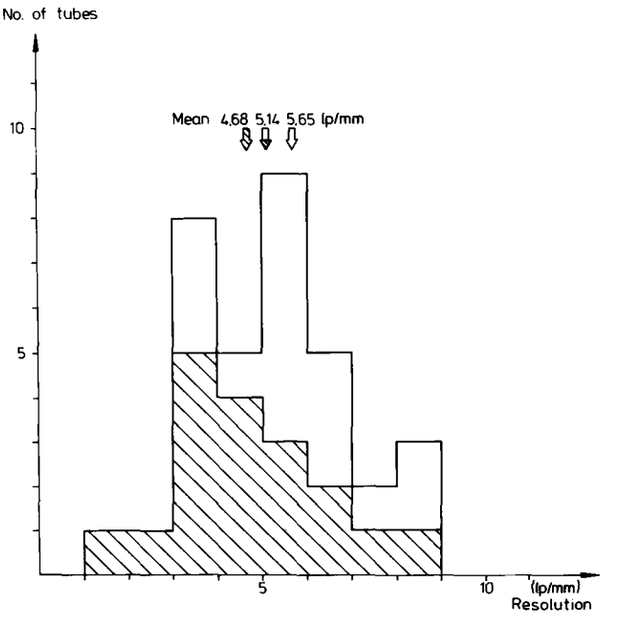

Fig. 7. Distribution of visual resolution (6 cm phantom). □ special tube (16). ▨ ordinary tube (18).

in Fig. 6 and the spectra of the tubes (RICCI et coll., HAUS et coll. 1977), and deviate from the values given in the literature (BICEHOUSE, WATSON, JENSEN & BUTLER 1978).

Discussion

The use of screen-film (vacuum) combinations should be increased since changing over to this type of system from non-screen films reduces the doses by a factor between 3 and 30, providing other improvements are made at the same time (HAUS et coll. 1979). If sufficient information is obtained by means of at the most 2 images per breast, the patient dose is reduced. Large reductions in doses can also be achieved by restricting the radiography to the diseased or symptomatic breast.

High skin doses (>20 mGy) can be reduced by making a number of improvements such as increasing the focus-film distance, reducing or removing altogether the voltage damping (pre-magnetization), removing the malfunctions in generators, replacing 1- and 2-pulse generators by multi-pulse or direct current generators, compressing the breast, increasing exposure voltages that are too low, using a screen-film (vacuum) combination instead of non-screen film, replacement of cassettes (vacuum) that give poor contact, renewal of old screens, minimizing exposure time when using a screen-film combination (SEELENTAG & PANZER 1978), no over-exposure of the film, and changing the developing process in accordance with the recommendations of the manufacturer so as to prevent over- or under-development of the films.

Since skin doses in mammary radiography may reach several hundreds of mGy per exposure, it has been proposed and recommended that the average absorbed dose to the breast should not exceed 6 mGy/year (HAGEMANN 1977) or 20 mGy/year (ELLIS 1972). A mean midline dose less than 5 mGy/view was recommended by the National Cancer Institute (BRESLOW et coll. 1977).

Although the use of screen-film combinations results in patient doses that are far lower than those obtained with non-screen films, the former method has the disadvantage that the contrast of the image is poorer. The reasons for the poor contrast (<10%) included the use of an ordinary tube, a total filtration of over 1 mm Al, a tube voltage of over 35 kV, excessive film density, use of a conventional screen-film cassette combination, the presence of a medium other than air, poor contact between the

screen and the film, and the fact that the development process had not been optimized.

The reasons for the poor resolution (<5 lp/mm) of the films were: the real (measured) size of the focus was large (>0.9 mm), too short a focus-film distance in relation to the focus size (the most usual reason), excessive film exposure, the use of a conventional screen-film cassette combination, and poor contact between the screen and the film.

One surprising finding was that in hospitals where the number of examinations was small the image quality was not inferior to that obtained elsewhere, a result which differs from observations made by WATSON. The number of patients examined per year did not appear to have any effect on the absorbed dose, either.

In some cases the image quality is affected more by the exposure time than by the focus size; the time must be short enough to prevent unsharpness due to patient movement. The reasons for long exposure times were too low kV, low mA, a slow increase of either current or voltage due to a fault in the generator, or their failure to reach the pre-set values, the use of a 2-pulse generator, too high total filtration, too long focus-film distance, poor contact between the screen and the film, an ageing screen, excessive film density and failure to optimize the development process.

Only 3 of the tubes examined had a focus size within IEC 336 tolerance limits. Action should therefore be taken to ensure that this does not arise. This can best be achieved if, at the time of asking for a quotation, the buyer also requests the measured values of the tube focus or foci.

The results show that a wide dispersion in the quality of the equipment existed in Finland. This is particularly well illustrated by the almost 5 000-fold difference between the highest and lowest surface doses. This is the cumulative result of a large number of factors, and exceeds the results previously obtained for measurement series covering several tens of equipments (BICEHOUSE, JANS, SHRIVASTAVA 1976, GROSS 1977, MILLER 1977, WATSON, JENSEN & BUTLER, U.S. Department of Health, Education and Welfare; Food and Drug Administration; Bureau of Radiological Health 1978, BATES & DEMIDECKI 1979, HAMMERSTEIN et coll.). It should be possible to reduce this dispersion without difficulty, and the aim could initially be to reduce the difference by at least a factor of a hundred or so. This aim can best be achieved by joint action by all the parties involved, and by stepping up monitoring and quality control. This can be implemented most efficiently by encouraging radiographic centres to take more active measures for quality control.

SUMMARY

The doses, the image qualities and the factors affecting these were determined for all equipments used for mammary radiography in Finland. It was found that the quality of the equipment tested varied greatly. This is particularly well illustrated by the 5 000-fold difference between the highest and lowest surface doses. Large differences in image quality were also found.

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