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Comparison of performance characteristics of conventional and K-edge filters in general diagnostic radiology

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Abstract. The performance characteristics of conventional and K-edge filters have been studied for the entire field of general diagnostic radiology. The problem of optimising the conflicting needs from patient dose, image contrast and exposure time was managed primarily by computer simulation. In comparison to conventional filters like iron or copper no significant advantages can be obtained with K-edge filters in practice except for the special circumstances of automatic fluoroscopy. The optimal choice of conventional filters is discussed. The different roles of backscattered radiation for skin dose and integral dose are demonstrated, and the necessity of correcting for increased backscatter following additional filtration is stressed. The potential for dose reductions by adding filtration has been found to be substantially smaller than the figures mostly reported. Finally some methodological problems of studies of this kind are pointed out.

1. Introduction

It is commonly known that the spectrum produced by an x-ray tube is a broad, 'white' spectrum. The 'soft' portions on the low-energy side have no, or only a slight, chance of reaching the image receptor whilst contributing excessively to patient dose. The 'hard' portions on the high-energy side which are advantageous in terms of patient dose are inferior in terms of producing good contrast.

Not surprisingly, the optimum is assumed to be found in the central part of the spectrum. This has been demonstrated by several authors (e.g. Oosterkamp 1961, Motz and Danos 1978, Carlsson 1979). A narrow range of optimal photon energies arises, especially if contrast media such as barium or iodine are used. Thus the best results would be expected with monochromatic radiation, but the intensities of conventional sources of monochromatic x-rays are not sufficient for imaging in diagnostic radiology (only recently the use of synchrotron radiation has been proposed (Rubenstein *et al* 1981)).

Therefore K-edge filters have been suggested as a possible means of producing quasi-monochromatic x-ray spectra. These filters are made of materials having the K-absorption edge in the desired central portion of the spectrum. K-edge filters act as 'bandpass filters' (figure 1) by suppressing both the soft (like any conventional filter) and the hard portions of the spectrum (due to the additional absorption by the K-shell electrons). Thus the most useful portion is selected.

Over the past 19 years a number of studies dealing with the effects of K-edge filters have been published (Richards *et al* 1970, Atkins *et al* 1975, Villagran *et al* 1978, Burgess 1981, Fleay *et al* 1982, Yamaguchi *et al* 1983, Webster 1984, Burgess 1985,

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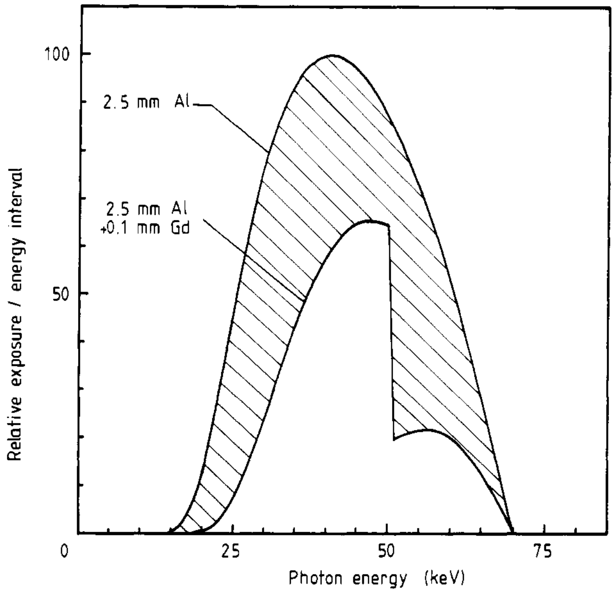

Figure 1. The principle of bandpass filtration with K-edge filters. The initial 70 kV spectrum filtered with 2.5 mm Al is shaped by an added filter of 0.1 mm Gd. The Gd filter supresses both the soft (like any conventional filter) and the hard portions of the spectrum (due to the K-absorption edge at 50.2 keV) to some extent. The area under each spectrum represents the relative entrance exposure per mAs.

Tyndall and Washburn 1987, Piotrowski 1987). Different filter materials—most of them rare earth materials, but also heavy metals like tungsten—have been proposed for various radiological techniques. The message found in each of these papers was something like 'patient dose cut to half without noticeable loss of image quality'. Consequently, advertisements have appeared for commercially available filters such as an erbium filter (Radiology 1986) or an 'Yttro Rare Earth Filter' (Diagnostic Imaging 1985) which was announced as a 'Major Breakthrough' by saving up to 70% in patient dose.

In 1985 we were first asked by customers for recommendations on how to usefully apply K-edge filters to their x-ray systems. The results of initial computer simulations, however, gave us some indications that the performance characteristics of conventional filter materials like copper or iron might be comparable to those of K-edge filters. Up until then Kuhn (1982, 1985) had been the only author to investigate the effects of both types of added filter materials. Except for iodine imaging at high tube voltages using a heavy holmium filter 250 μm thick, he could find no significant advantages of K-edge filters over conventional filters.

We therefore started a comprehensive study based primarily on computer simulations in order to clarify whether the asserted superiority of K-edge filters was justified. After we had finished the simulation part of our study, Koedooder and Venema (1986) who investigated one typical radiological situation independently came to the same conclusions. In this paper there are two aims in an ongoing controversy on the optimal choice of added filter materials: First, to find definitive answers for the entire range of applications in general diagnostic radiology (except mammography), and second, to discuss the potential of reducing patient dose following the application of added filtration by including all relevant influences.

2. Method

2.1. Computer simulations

The investigation was primarily performed using the spectral simulation technique. X-ray spectra were generated for a tungsten anode x-ray tube with an anode angle of 13° at constant potential by a computer program based on the method of Birch and Marshall (1979). A second computer program allows us to trace the spectral changes which take place when an x-ray beam passes through filters, human tissue and contrast media until it is detected by an image receptor. The tabulated x-ray cross sections from McMaster *et al* (1969) have been used to evaluate the interaction of x-rays with matter.

In table 1, the parameters used in this study and their ranges of variation are listed. K-edge filters were selected with K-absorption edges in steps of approximately 10 keV. Holmium, the K-edge filter of choice in the papers published by Kuhn (1982, 1985), was also studied. The selection of conventional filters was extended to yttrium which was claimed to be superior by Wang *et al* (1984).

Table 1 Parameters used in this study and their ranges of variation. For further details see text.

Parameter	Range of variation	
9 filter materials	Conventional	K-edge filters
	Aluminium Iron Copper Yttrium	Lanthanium Gadolinium Holmium Thulium Tungsten
3 filter thicknesses	0.1, 0.2 and 0.3 mm CHE (in addition to inherent filtration of 1 mm Al)	
7 tube voltages	40–100 kV in steps of 10 kV	
6 object thicknesses	5–30 cm tissue according to ICRP 23 (1975) in steps of 5 cm	
3 image receptors	$CaWO_4$, Gd_2O_2S and BaFCl screens	
2 contrast media	1 mm Al and 0.02 mm iodine (10 mg cm^{-2})	

Each filter was added to an inherent filtration of 1 mm Al which is the aluminium hardness equivalent of the materials used in a typical tube assembly with a glass-walled x-ray tube. The filter thicknesses have been chosen with a hardness equivalent to 0.1, 0.2 and 0.3 mm Cu; the spectral matching was made at an effective energy of 30 keV. The concept of copper hardness equivalent (CHE) follows the same basic ideas published by the author in an earlier paper upon aluminium equivalence (Nagel 1986). For conventional filters the resulting thicknesses are very close to the values from a recent paper by Jennings (1988) for qualitatively equivalent filters (see table 2).

If K-edge filters are used at tube voltages numerically lower than their K-edge energy E_K, the same applies as for conventional filters. Once the K-edge interferes with the spectral region of interest, a complete spectral matching is no longer possible. Thus only the shapes of the spectra below the K-edge are identical for both the K-edge filter and the 'equivalent' copper filter. This definition is in accordance with Bäuml (1977) and the IEC standard 407 (IEC 1973), both intending equivalent removal of

Table 2. Filter thicknesses being 'hardness equivalent' to 0.2 mm copper. Our copper hardness equivalent was determined for an effective energy of 30 keV. The location of the K-absorption edge was taken from McMaster *et al* (1969).

Filter material	K-edge (keV)	'Equivalent' thicknesses (mm) This work	Jennings†	Koed/Venema‡
Aluminium (Al)	1.56	7.10	7.20	5.77
Iron (Fe)	7.11	0.302	0.302	0.305
Copper (Cu)	8.98	0.200	0.200	0.200
Yttrium (Y)	17.1	0.192	0.188	0.184
Lanthanium (La)	38.9	0.314	—	0.105
Gadolinium (Gd)	50.2	0.176	—	0.164
Holmium (Ho)	55.6	0.138	—	0.140
Thulium (Tm)	59.4	0.118	—	—
Tungsten (W)	69.5	0.046	—	0.043

† Quality equivalent thicknesses reported in the recent work of Jennings (1988) refer to weighting by a 65 kVp spectrum.

‡ Values taken from Koedooder and Venema (1986) refer to equal contrast and a twofold increase in tube load compared to a reference configuration (70 kV/3 mm Al/20 cm water/$CaWO_4$ screen).

the low-energy portions of the pertaining spectra. Because of the method used to compare filter materials, the exact thickness of K-edge filters is not very crucial. Conditions which cannot be reasonably compared are thus avoided.

The patient is simulated by uniform tissue layers with thicknesses ranging from 5 to 30 cm. The tissue composition was chosen according to ICRP 23 (1975); calculations could have been performed using simply water or PMMA (better known as lucite) because the comparison of different filters is not very material dependent.

The selection of intensifying screens represents the range of K-absorption edges to be found in order to study any possible interference with the K-absorption edge of the filters. The mass thicknesses per pair of screens are typical for standard/regular film-screen combinations (see table 3). The photon absorption and energy transfer in the screens were treated according to Birch *et al* (1979) by excluding all the fluorescent K-x-rays having photon energies greater than 25 keV.

The two contrast media studied here were aluminium (representing bone material) and iodine, the latter showing a K-absorption edge at 33.2 keV. Their thicknesses result in contrast numbers of the order of 5%. For low contrasts the relative ranking of the filter materials under investigation is independent of the actual thickness of the detail to be imaged.

Table 3. Characteristics of the image receptors used in this study. The screen-film speed is the reciprocal value of the air kerma (in mGy) required to produce a net optical density of 1 at specified conditions.

Screen material	K-absorption edge of heavy element (keV)	Mass thickness per pair ($mg\,cm^{-2}$)	Screen-film speed
BaFCl	37.4	80	200
Gd_2O_2S	50.2	80	200
$CaWO_4$	69.5	60	100

The calculations were made in the narrow beam approach, that is by neglecting secondary effects like scatter. The same applies to photon noise, another important characteristic of image quality, which has not been taken into account. Both can be justified by the fact that the comparison of filters will be carried out for contrasts being at least almost equal. This implies that the mean energies of the pertaining spectra are almost equal, too, and that differences in relative noise numbers and scatter fractions are negligible.

For the evaluation of patient dose, both entrance dose X (expressed in exposure) and integral dose D have been calculated; the same definitions have been used as stated in equations (6) and (7) of the paper of Koedooder and Venema (1986). Backscatter was usually neglected because the mean energies produced by the added filters to be compared are almost equal. It was taken into account, however, when added filters were compared to the reference filtration of 2.5 mm Al.

The contrast C used in this study is expressed by

$$C=\frac{E_{\mathrm{abs}_1}-E_{\mathrm{abs}_2}}{E_{\mathrm{abs}_1}+E_{\mathrm{abs}_2}} \tag{1}$$

with E_{abs_1} and E_{abs_2} being the energy absorption per unit area of the intensifying screen at the locations corresponding to the contrast medium to be imaged and the surrounding tissue.

In order to compare configurations resulting in slightly different values for contrast C, entrance dose X or integral dose D, a performance index G proposed by Gajewski and Reiß (1974) was used:

$$G_1=C^2/D \tag{2}$$

and

$$G_2=C^2/X \tag{3}$$

which balances minor advantages in contrast against minor detriments in dose and vice versa. This figure is closely related to what is known as 'signal-to-noise ratio for constant dose' used for example by Motz and Danos (1978). It should be clear that G becomes less valid when comparing configurations with significantly different values of contrast and dose.

2.2. Experimental

A limited number of configurations were investigated experimentally which had been found to be representative. The purpose of this was to make a spot check of the validity of our computer simulations. All measurements were carried out in narrow beam geometry on a phantom made of PMMA (chemical formula: $[C_5H_8O_2]_n$) using an ionisation chamber for the detection. Additional calculations were made to simulate the specific choice of phantom material and detector used during the experiments.

3. Comparison of different filter materials

When looking for any other choice than the usual filtration of 2.5 mm Al, the impacts on the essential performance characteristics which are patient dose, image quality (represented by contrast) and tube load (or exposure time) must be valued likewise (see figure 2). We therefore have to deal with an optimisation problem as these

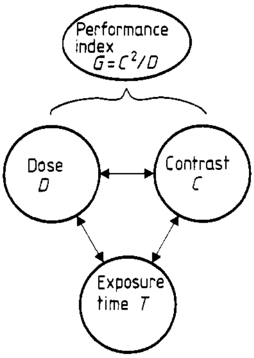

Figure 2. Patient dose D, image contrast C and exposure time T are conflicting needs in the optimisation of filtration in diagnostic radiology. The performance index G (Gajewski and Reiß 1974) enables us to compare configurations with slightly different values of dose and contrast.

magnitudes can never be best simultaneously. Under these circumstances, a comparison of conventional and K-edge filters, of K-edge filters having different K-edge energies, or filters with different thicknesses may easily lead to a comparison of apples and oranges unless a suitable scale is used.

Koedooder and Venema (1986), by studying only one typical configuration (i.e. the imaging of iodine contrast in an object of 20 cm tissue thickness with a 70 kV spectrum filtered by 3 mm Al), calculated the filter thicknesses and tube voltages for a variety of added filter materials that fulfilled the constraints of equal contrast and the same increase in tube load in a self-optimising procedure and ranked them according to their ability to reduce patient dose. We took a somewhat different approach. For each filter under investigation we simulated approximately 750 different configurations of selected filter thicknesses, tube voltages etc, (see table 1), thereby producing a comprehensive set of permanent data which can be further analysed for a number of additional tasks. The way in which the comparisons are performed is as follows.

3.1. *Comparison of conventional and K-edge filters*

As the application of added filtration is inevitably associated with the penalty of increased tube load, a proper comparison must necessarily take into consideration such a constraint. We therefore compared added K-edge and conventional filters, represented by Cu, at equal exposure times which refer to a constant amount of energy absorption in the intensifying screens. In addition, exposure time is a characteristic which is 'neutral', as patient dose and image quality are the goals which are usually in conflict with each other. In our approach the second constraint (usually equal contrast) which is necessary to make a ranking for a problem with three performance characteristics involved can be fulfilled only fortuitously in some cases. We therefore make use of the performance indices G_1 and G_2 within reasonable limits, thus ranking different filters according to their performance index. An example of this procedure is given in § 4 (see figure 3).

3.2. *Comparison of different conventional filters*

Our set of data also enables us to answer the question for the conventional filter material of choice. A proper comparison can be made in the way described by Jennings

(1988), by evaluating qualitatively equivalent filter thicknesses and ranking them according to their relative transmission. Contrary to the situation with K-edge filters, a spectral matching relative to a given filter, e.g. 0.2 mm Cu, is possible which can be satisfied within small tolerances with a single filter thickness for a broad range of applications.

An alternative method is to carry out the comparison as described in § 3.1. This procedure allows for the compensation of small differences in the resulting values for dose and contrast if the filter thicknesses have not been selected to be strictly equivalent. This also applies for the filter thicknesses reported by Jennings (1988) because a single value does not completely satisfy the spectral matching for a large range of tube voltages and thicknesses of filters and objects. The ranking is once again made according to the resulting performance indices.

3.3. *Comparison of added and standard filtration*

When comparing any added filtration to the standard filtration (i.e. 2.5 mm Al), only the constraint of equal contrast is applicable, thereby evaluating the benefits (dose reductions) and the penalties (increased tube load/exposure time) following the application of added filtration.

4. Results

4.1. *K-edge filters versus conventional filters*

4.1.1. Computer simulations. Including the reference data for the standard filtration of 2.5 mm Al, approximately 7000 configurations were simulated, arranged, plotted and interpreted. In order to manage this vast number of results, we will restrict ourselves to show a typical result, to deduce the general tendencies and finally to demonstrate a configuration which is the most favourable for K-edge filters.

Figure 3 shows a typical performance diagram. In the upper part, the integral dose D to the patient for an object thickness of 15 cm is plotted in arbitrary units as a function of the exposure time T resulting from a given configuration. T has been evaluated for an x-ray system rated to 80 kW at 100 cm focus-to-film distance (FFD) with constant energy absorption in a $CaWO_4$ intensifying screen with a speed 100 screen-film combination. Falling load operation at exposure times exceeding 100 ms as well as the limited emission at low tube voltages in accordance with the rating charts of typical diagnostic x-ray tubes have been taken into account. The total transmission of the material layers situated between the patient and the image receptor (i.e. table top, automatic exposure control chamber and anti-scatter grid) was taken as 1/3.

In this example, results have been plotted for Cu, La and Gd (filter thicknesses of 0.2 mm CHE) which have been obtained by varying the tube voltage in steps of 10 kV (see dots), starting at 100 kV on the left. By plotting the other performance characteristics against the exposure time, it becomes evident which combinations of tube voltages, filter materials and thicknesses fall inside the range of exposure times suitable for a given imaging task.

The upper diagram exhibits an integral dose produced by the La filter which is somewhat higher by 10% in the medium range of tube voltages whereas the resulting dose is the same for both the Gd and the Cu filter. In a similar way the contrast C

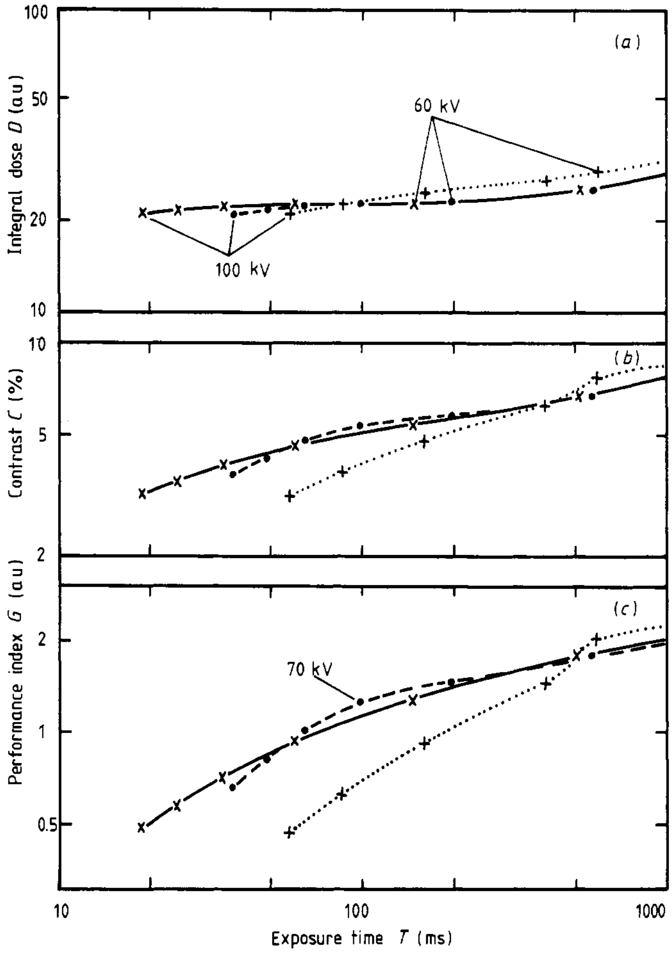

Figure 3. A typical result of the spectral simulation of integral dose *D* (*a*), contrast *C* (*b*) and performance index *G* (*c*) for Cu, La and Gd filters with 0.2 mm CHE. The resulting magnitudes are plotted against the exposure time *T* under specified conditions (see text) with the tube voltage varying in steps of 10 kV, starting at 100 kV on the left. The detail to be imaged in an object 15 cm thick is a layer of 1 mm Al. The filters are: ×, 0.200 mm Cu; +, 0.314 mm La; ●, 0.175 mm Gd.

(in %) resulting from a detail made of 1 mm Al can be plotted as shown in figure 3(*b*). This figure reveals that the contrast obtained by using the Gd filter is somewhat better by 5 relative percent (i.e. % of %) in the region around 70 kV but—at higher tube voltages—likewise worse than for the Cu filter. For the La filter the same holds with the exception that higher contrasts are obtained at tube voltages lower than 60 kV and that it behaves much worse at high voltages.

Finally the resulting performance index G_1 is shown in figure 3(*c*). A slightly better performance can be observed for Gd in the voltage range around 70 kV. This difference of 10% in performance index is at the lower limit of what can be regarded as a significant difference in practice. At higher voltages the Cu filter offers a better performance. The La filter is superior in a range which is not applicable in normal practice due to exposure times being much too long. At lower exposure times, i.e. at higher voltages, the performance is considerably inferior.

The results of all other configurations in our study can be summarised and the following general tendencies which favour the performance of K-edge filters over conventional filters can be deduced:

(i) Only those K-edge filters having their K-edge at about 50 keV (e.g. Gd, Ho) exhibit a slightly better performance; K-edge filters with a higher atomic number Z are not sufficiently selective; those with a lower Z are superior only at low voltages, resulting in exposure times being much too long.

(ii) The optimal tube voltage range lies between 70 and 80 kV; at lower voltages the K-edge is not effective, while at higher voltages a significantly inferior performance must be noted.

(iii) The greater the filter thickness, the more significant is the gain in performance of K-edge filters under optimised conditions.

(iv) The somewhat better performance of K-edge filters is most pronounced with thin objects, e.g. in paediatric radiology.

(v) In combination with contrast media showing a K-absorption edge themselves like iodine and barium, the performance is slightly better than with other contrast media.

(vi) K-edge filters fit best to image receptors having an absorption edge themselves that interferes least in the spectral region of interest (e.g. $CaWO_4$ at 69.4 keV or Y_2O_2S at 17.1 keV); using Gd filters and Gd_2O_2S screens is somewhat counter-productive.

In figure 4 the configuration is presented which is the most favourable for a K-edge filter in terms of performance. This means using a Gd filter with a 'hardness equivalent' to 0.3 mm of Cu for the imaging of iodine in an object of 5 cm thickness in combination with a $CaWO_4$ intensifying screen. This results in a gain of about 20% in performance index G_1 over Cu for voltages near 70 kV due to a better contrast (by 7 rel.%) and a lower integral dose (by 5%). All other configurations being investigated exhibit either smaller or no advantages over conventional filters at all.

4.1.2. Experimental verification. For the experimental tests Cu and Gd filters with approximately 0.1 mm CHE, purchased from Goodfellow Metals Ltd, and object thicknesses of 6.5 and 16 cm of PMMA were used. The actual filter thickness was determined by precision measurements of the mass m and the area A of each filter. Both 1 mm Al and 0.02 mm iodine have been taken as contrast media. The tests were performed in our dosimetry laboratory using a highly stabilised Philips MG 324 x-ray generator together with a Philips MCN 321 x-ray tube in the range 50–100 kV. Measurements of entrance and exit exposure were carried out in narrow beam geometry using a secondary standard dosemeter (NP 2100 electrometer with TK 30 cc ionisation chamber, both obtained from the Austrian Research Center, Seibersdorf). The relative differences for exposure time, entrance exposure, Al and iodine contrast between the two filters were found to be the same both for the measured and the calculated results within the usual bandwidth of experimental errors (see table 4).

4.2. *Conventional filter materials*

The comparison between the conventional filter materials being studied (see table 1) at equal exposure times reveals equal performance for Cu and Fe filters. Both Al and Y filters are inferior to these materials. The results of a comparison relative to Cu for equal contrasts are shown in table 5. Contrary to the values given in table 2, the filter thicknesses equivalent to 0.2 mm Cu have been slightly re-adjusted for this purpose.

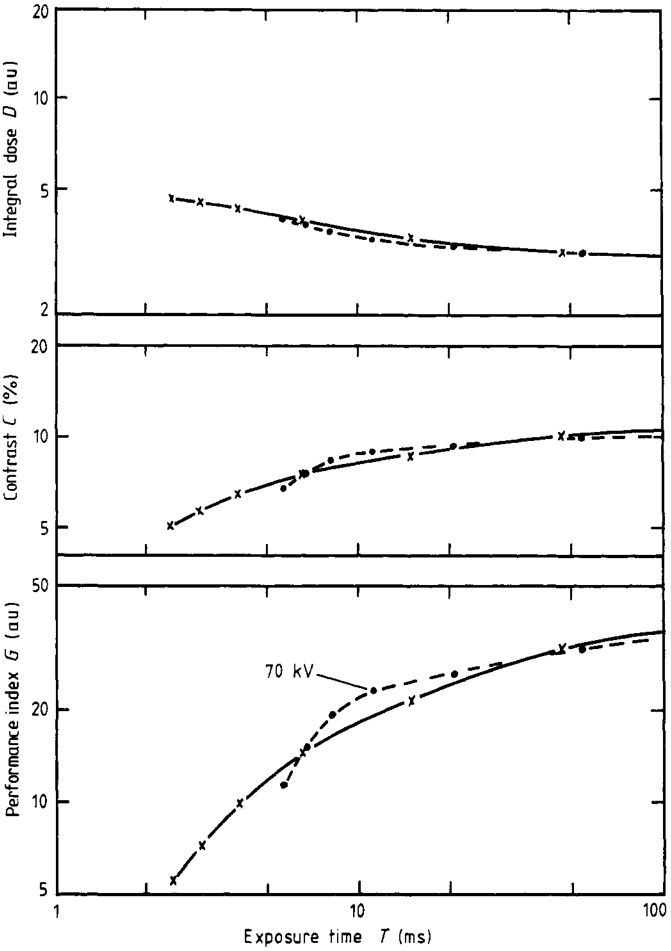

Figure 4. The most favourable result for a K-edge filter in comparison to a conventional filter for Gd and Cu with 0.3 mm CHE. The detail to be imaged in an object 5 mm thick is a layer of 0.02 mm iodine. All other conditions are the same as described in figure 3. The filters are: ×, 0.300 mm Cu; ●, 0.263 mm Gd.

Table 4. Comparison of calculated and measured values of exposure time $T_{\rm rel}$, entrance dose $X_{\rm rel}$, Al contrast $C1_{\rm rel}$ and iodine contrast $C2_{\rm rel}$ for a 0.088 mm Gd filter relative to a 0.097 mm Cu filter (inherent filtration: 1 mm Al).

	$T_{\rm rel}$		$X_{\rm rel}$		$C1_{\rm rel}$		$C2_{\rm rel}$	
U (kV)	calc.	meas.	calc.	meas.	calc.	meas.	calc.	meas.
(*a*) Object: 6.5 cm PMMA								
60	1.15	1.18	1.02	1.01	1.03	1.02	1.03	1.01
80	1.29	1.30	1.06	1.05	1.10	1.07	1.09	1.06
100	1.36	1.37	1.06	1.05	1.10	1.09	1.10	1.08
(*b*) Object: 16 cm PMMA								
60	1.19	1.20	1.05	1.03	1.04	1.09	1.05	1.01
80	1.42	1.39	1.15	1.12	1.11	1.10	1.12	1.13
100	1.46	1.44	1.13	1.11	1.08	1.06	1.09	1.12

Table 5. Comparison of the performance characteristics of filters relative to a 0.200 mm Cu filter for object thicknesses between 10 and 30 cm. Inherent filtration: 1 mm Al. Detector: 80 mg cm^{-2} Gd_2O_2S. (T = exposure time; $C1$ = Al contrast; $C2$ = iodine contrast; D = integral dose; X = entrance dose).

U (kV)	T_{rel}	$C1_{rel}$	$C2_{rel}$	D_{rel}	X_{rel}
(*a*) 7.34 mm Al					
50	1.300	1.000	1.001	0.996	0.987
70	1.311	1.001	1.002	1.001	0.998
100	1.312	1.001	1.001	1.001	1.000
(*b*) 0.306 mm Fe					
50	1.000	0.999	1.000	0.997	0.993
70	1.002	1.000	1.001	1.000	0.997
100	1.003	1.001	1.001	1.000	1.000
(*c*) 0.18 mm Y					
50	0.999	1.003	1.000	1.040	1.383
70	1.000	1.001	0.999	1.009	1.134
100	0.997	0.999	0.998	1.002	1.045

The Al filter exhibits a 'throughput' defiency at a given tube voltage, leading to an increase in exposure time of 30% for 7.34 mm Al (table 5(*a*)). The other performance characteristics are the same as for Cu within very small tolerances. The almost perfect equivalence of 0.306 mm Fe with 0.2 mm Cu is demonstrated in table 5(*b*). The comparison of 0.18 mm Y with 0.2 mm Cu in table 5(*c*) reveals equal exposure times and contrasts, but considerably higher values for the entrance exposure, primarily at low tube voltages, and slightly higher values for the integral dose.

4.3. Dose reductions achieved by additional filtration

The potential of additional filtration to reduce the radiation dose to the patient is demonstrated in figure 5. Cu filters of various thicknesses were added to the inherent filtration of 1 mm Al and are compared to a typical reference configuration (i.e. 70 kV/2.5 mm Al). In order to maintain the contrast $C1$ for a detail of 1 mm Al, a reduction of the tube voltage is necessary which is largest for thick filters and thin patients.

The relative dose for object thicknesses between 10 and 30 cm and added filter thicknesses between 0.1 and 0.3 mm Cu is shown in figure 5(*a*) for the entrance dose and in figure 5(*b*) for the integral dose. Reductions in entrance dose are typically of the order of 35%, reaching 50% for both thick patients and thick filters. Reductions in integral dose are considerably smaller (typically 13%, and up to only 20%). In both cases, backscatter effects have not been taken into account.

The relative increase of the backscatter factor which is caused by the hardening of the entrance beam was determined experimentally in terms of exposure for a typical field size of 20 cm × 20 cm. In order to evaluate the BSF related to energy fluence, Monte Carlo simulations have been made which allowed us to convert the measured data. The consequences of taking backscatter into account is demonstrated in figure 5(*c*) (entrance dose) and 5(*d*) (integral dose).

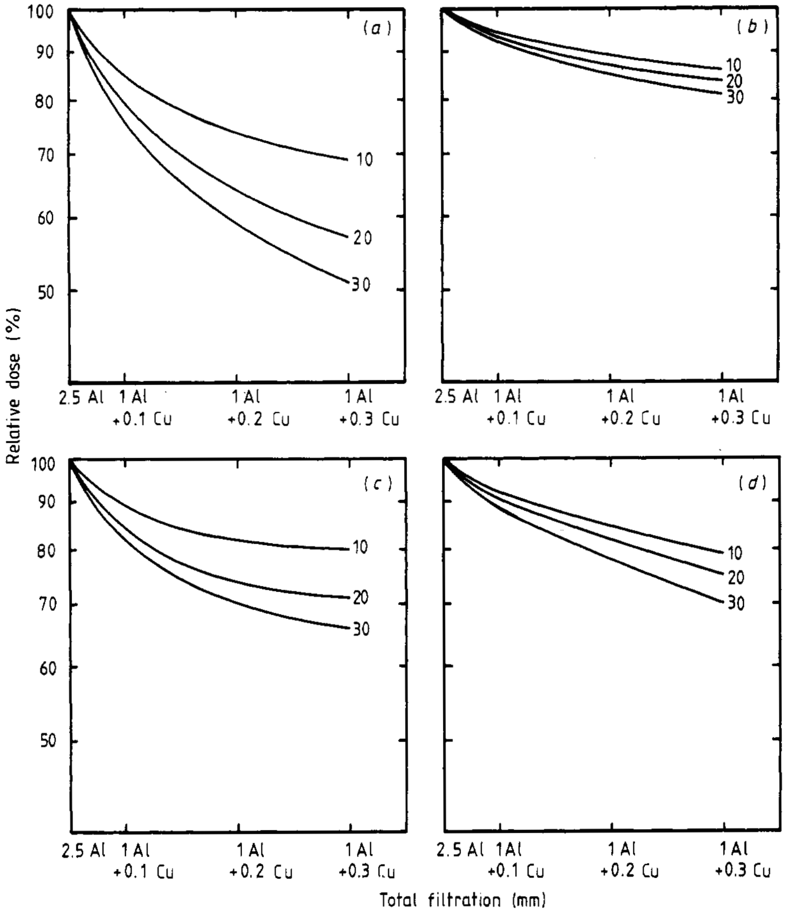

Figure 5. The potential for dose reductions is shown for various object thicknesses (cm) in comparison to a reference configuration at 70 kV filtered with 2.5 mm Al. The contrast for a detail of 1 mm Al is maintained for each configuration by appropriately adjusting the tube voltage. The entrance dose and the integral dose are shown in (*a*) and (*b*), respectively, without taking the increased amount of backscatter for harder beams into account. In (*c*) and (*d*) the results are shown after correction for backscattered radiation from a 20 cm × 20 cm field.

A higher BSF in terms of exposure (by up to 15%) leads to an increase in skin dose, thus making the reductions in terms of skin dose smaller than in figure 5(*a*) (typically 25% and maximum 35%). The higher BSF in terms of energy fluence (by up to 10%) effects a reduction in energy imparted to the patient, thus making the reductions in terms of integral dose larger than in figure 5(*b*) (typically 20% and maximum 30%).

5. Discussion

5.1. K-edge filters versus conventional filters

Our study based on a great variety of configurations reveals that there is nothing special about K-edge filters. Our findings are in contradiction to most other authors in the field who claimed a superiority of K-edge filters over conventional filters. This essentially turns out as the result of an inadmissable comparison between a heavy K-edge filter and a conventional filter of only normal thickness such as 2.5 mm Al.

The general assumption that K-edge filters might be superior due to their special band-pass filtering properties does not hold. The selectivity which can be obtained with K-edge filters of reasonable thicknesses (i.e. up to 0.3 mm CHE) is not sufficient. The same can be managed with an appropriate conventional filter as well, if only lower tube voltages are applied in order to maintain the contrast level (at equal increase in tube load). This is demonstrated in figure 6 by the patient entrance spectrum and the absorbed energy spectrum in an intensifying screen for Gd and Cu filters in a typical application.

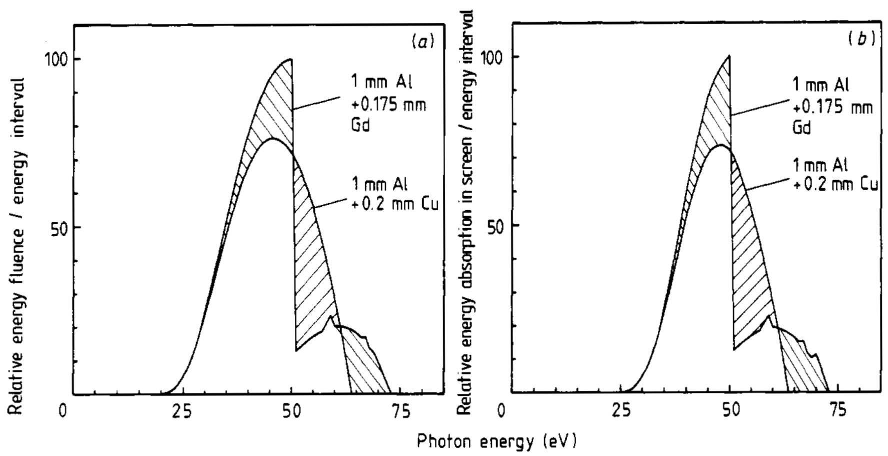

Figure 6. The energy fluence entrance spectra (*a*) and the energy absorption spectra within the $CaWO_4$ screen of 60 mg cm^{-2} mass thickness (*b*) for Cu and Gd filters of 0.2 mm CHE in addition to 1 mm Al inherent filtration. Both spectra are drawn to scale for equal exposure time *T*. The contrast for a detail of 1 mm Al in an object 20 cm thick which is produced by the standard filtration of 2.5 mm Al at 70 kV is maintained at 64 kV with the Cu filter and at 73 kV with the Gd filter. Integral and entrance dose as well as the performance index differ only by minor amounts (see also table 6(*a*)). This is shown by the differently hatched areas indicating that the conventional filter in combination with a lower tube voltage practically compensates the limited selectivity of the K-edge filter.

The corresponding numerical values are listed in table 6 relative to the reference configuration (70 kV/2.5 mm Al). The example shows that the tube voltage must be increased in order to obtain optimal results with K-edge filters. This is in good agreement with the findings of Koedooder and Venema (1986). The applicability of K-edge filters is impaired by the restriction to tube voltages in the range between 70 and 80 kV. Added filters made from conventional materials therefore offer a greater flexibility.

Our results indicate that K-edge filters are slightly superior in applications with thin objects, i.e. in paediatric and in dental radiology. The advantages are not very large and depend on the coincidence with other favourable conditions. Added filtration of any kind, however, should not be recommended for a technique like dental radiology using x-ray tubes with very limited power.

For practical reasons K-edge filters turn out to be more suitable in automatic fluoroscopy. Contrary to screen-film radiography where the tube voltage can be

Table 6. Comparison of the performance characteristics of Gd and Cu added filtration relative to the standard Al filtration. The inherent filtration is 1 mm Al; object: 20 cm soft tissue; image receptor: 60mg cm^{-2} $CaWO_4$. (t_{add} = added filter thickness, U = tube voltage, T = exposure time, C = contrast, D = integral dose, X = entrance exposure, G_1 = performance index (related to D) and G_2 = performance index (related to X); correction for backscatter not yet included.

Filter	t_{add} (mm)	U(kV)	T_{rel}	C_{rel}	D_{rel}	X_{rel}	$G_{1_{rel}}$	$G_{2_{rel}}$
(*a*) Contrast medium: 1 mm Al								
Al	1.5	70	1.000	1.000	1.000	1.000	1.000	1.000
Gd	0.175	73	2.290	0.998	0.877	0.625	1.136	1.592
Cu	0.2	64	2.273	0.971	0.856	0.597	1.102	1.581
(*b*) Contrast medium: 0.02 mm iodine								
Al	1.5	70	1.000	1.000	1.000	1.000	1.000	1.000
Gd	0.175	77	1.892	0.996	0.848	0.579	1.170	1.712
Cu	0.2	66.5	1.896	0.982	0.841	0.557	1.147	1.729

selected independently, the tube voltage in automatic fluoroscopy is automatically increased if additional material is brought into the beam path. The application of conventional added filters, however, requires somewhat lower tube voltages compared with normal practice. Thus the control characteristics are generally in favour of the voltage requirement of K-edge filters. How well these can be met, however, depends on the voltage-current characteristic of a given piece of equipment.

Our findings are by no means anticipated by the special choice of filter thickness 'equivalence' made here for reasons pointed out earlier. Our results may be interpreted in such a way that for any K-edge filter of a given thickness a copper filter was found which, in practice, was at least comparable in performance. The comparison with filter thicknesses which were found by Koedooder and Venema (1986) in a somewhat different approach reveals very similar values for all situations where a K-edge filter seriously competes with a conventional filter (see table 2). This also becomes apparent from the example shown in figure 6. Our concept of copper hardness equivalence which results in spectra of equal shape as long as no K-absorption edges are involved therefore represents a good approach in the opposite case, too, in order to make a classification of the 'heaviness' of a K-edge filter.

5.2. Conventional filter material of choice

It is well known that materials with a higher atomic number Z than Al offer a better ratio of filtering to attenuating properties (see for example Nagel 1986). With increasing Z the break-even point of photo absorption and total scatter occurs at higher photon energies. Total scatter is much less energy dependent than photo absorption where $\mu(E)$ varies approximately with E^{-3}. The stronger the energy dependence of $\mu(E)$, however, the better the filtering power of a (conventional) 'high pass' filter. As the exponent of the energy dependence of $\mu(E)$ for photo absorption slowly decreases with growing Z, the optimal filter material should be expected somewhere in the middle of the periodical system. The upper limit for Z, however, is set by the interference of the K-absorption edge of a given material within the spectral region of interest. Thus the range of optimal filters is found in the area of the transition elements up to $Z = 30$, i.e. materials like Fe, Cu and Zn. Our conclusions upon the conventional filter material

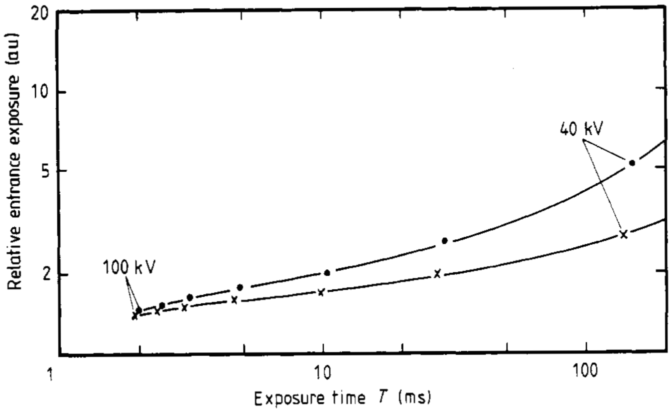

Figure 7. The transparency of pseudo K-edge filters like yttrium for photons with energies lower than E_K results in an undesirable increase in skin dose unless these filters are 'unprimed' by using them in combination with a certain amount of basic Al-like filtration. In this example, the entrance dose to an object 5 cm thick is compared for Cu and Y filters with 0.2 mm CHE, both added to 1 mm Al inherent filtration. The exposure times are valid for a $CaWO_4$ intensifying screen under the same conditions as in figure 3. After being 'unprimed', these filters are no better than filters made from Cu or Fe. The filters are: ×, 0.200 mm Cu; ●, 0.192 mm Y.

of choice are in excellent agreement with Kuhn (1982), Koedooder and Venema (1986) and Jennings (1988).

Filter materials like Y and Mo with K-absorption edges at 17.1 and 20 keV, respectively, although potentially useful as true K-edge filters for mammography, are a bad choice in general diagnostic radiology due to their transparency to photons with energies lower than E_K. The low-energy portions transmitted by these pseudo-K-edge filters result in an undesirable increase in skin exposure as is shown for Y in table 5(*c*). The same holds for the 'NIOBI-X'-filter which has been promoted just recently by RadRed Laboratories (1988) as another 'progressive breakthrough in patient radiation reduction'. Niobium ($Z = 41$), however, is situated just between Y ($Z = 39$) and Mo ($Z = 42$) in the periodical system of elements.

After being 'unprimed' by applying Y and Mo filters in combination with at least 0.08 and 0.13-mm Cu, respectively, these filters are by no means superior to Cu. This has also been found experimentally by Meydam *et al* (1985) which is contrary to the study by Wang *et al* (1984). They claimed a considerable superiority of a filter made of 0.1 mm Y+3 mm Al, thereby giving the foundation for the 'major breakthrough' advertisement in Diagnostic Imaging (1985). In the meantime, Nelson and Jennings (1986) have demonstrated a number of major flaws in almost every aspect of the comparison performed in this study which have biased the results strongly in favour of the Y filter. There is nothing to add to this critical review as our own results and a further analysis of the Wang *et al* data lead to identical conclusions.

5.3. Entrance dose versus integral dose

There is no doubt that dose reductions can be achieved without any loss in contrast by using added filters at an accordingly adjusted tube voltage though at the expense of an increased tube load or exposure time, respectively. Dose reductions have mostly been reported in terms of entrance exposure which can easily be measured. Except for radiological techniques where the entrance dose exceeds a critical level as e.g. in cardiac investigations, the integral dose (or energy imparted) is more closely related to radiation risk (Boag *et al* 1976). The conversion factor from exposure to energy fluence, however, is energy dependent. This leads to dose reductions in terms of mean absorbed dose being much smaller as long as backscatter effects have not been taken into account. Up to this point our findings are in good agreement with Koedooder and Venema (1986).

Backscatter cannot be neglected, however, when the dose reductions by additional filtration are compared with the standard filtration of 2.5 mm Al. The considerable dependence of the backscatter factor on beam quality has been shown for radiotherapy up to 100 kV in a number of publications (see e.g. Cohen (1972) and Grosswendt (1984)). At this point the completely different roles that backscatter plays in the determination of skin dose and integral dose, respectively, deserves special mention. Radiation backscattered from inside the patient increases the skin dose, i.e. the backscatter fraction must be added to the entrance dose. For the energy balance, however, backscatter represents a loss, i.e. the backscatter fraction related to the energy fluence (being smaller than the fraction related to exposure) must be subtracted from the incident energy fluence. This important difference has never been taken into consideration in any of the papers dealing with the beneficial aspects of additional filtration.

For the examples shown in figure 5 the results for the two different aspects of patient dose after correction for backscatter effects have thus become more similar. Nevertheless, the potential for dose reduction is considerably smaller than the maximum figures that are usually reported. This puts the benefits of additional filtration into a somewhat different perspective, keeping in mind the necessity for changes from common radiological practice.

5.4. Some final remarks on methodological problems

Quite obviously, proper comparisons can be performed only under clearly defined and relevant circumstances. The way in which this can be managed successfully for the delicate task of comparing conventional and K-edge filters has been shown by us as well as by Koedooder and Venema (1986), although the approaches are slightly different. A comparison at equal tube voltages which was and still is common practice in most of the related studies is inappropriate as the shapes of the spectra can differ considerably.

The determination of equal contrast is the most crucial point in experiments. In the study of Koedooder and Venema where a relative contrast of 1.00 refers to a difference in optical density of 0.27, the typical uncertainty in film densitometry of ± 0.01 corresponds to an error in measured contrast of ± 3 relative per cent. In our experiments, a dosimetric error of only $\pm 0.5\%$ leads to contrast errors of the order of ± 5 relative per cent. The accurate knowledge of the thickness of a given filter is another problem which primarily affects the determination of equal tube load. Thicknesses of filter sheets are usually stated by manufacturers like Goodfellow Metals Ltd to within $\pm$ 10% uncertainty only.

These problems are easily avoided in computer simulation studies where random errors are absent. Furthermore, computer simulation is the only chance to perform studies requiring the investigation of several thousands of different configurations. The validity of computer simulations depends primarily on the set of attenuation coefficients which are used, secondly on the correct modelling (e.g. to what extent effects like scatter, fluorescence radiation and photon noise are of importance) and least on the set of basic x-ray spectra if the study is of only a comparative nature.

Although there may be some uneasiness left from an experimentalist's point of view, our experience of many years with both methods leaves no doubt that simulation techniques are the most appropriate and sufficiently correct for comparative studies like the one presented in this paper.

6. Summary and conclusions

We have investigated the performance characteristics of conventional and K-edge filters in general diagnostic radiology. This has been performed for a comprehensive and representative selection of filter materials and thicknesses, of tube voltages, object thicknesses, image receptors and contrast media. Our results, which are primarily based on computer simulations, have been verified experimentally for a limited number of selected cases. Our findings have taken into account the impacts on patient dose, image contrast and exposure time. Our conclusions are as follows:

(i) In screen-film radiography K-edge filters offer no significant advantages over optimal conventional filters. A slightly better performance is observed only under very special circumstances. In automatic fluoroscopy, however, the impacts of an automatically increased tube voltage caused by any added filter are better managed by K-edge filters like gadolinium and holmium.

(ii) Optimal conventional filters are found with atomic numbers Z between 25 and 30, e.g. iron and copper, offering a better transparency than hardness-equivalent Al filters. Tube voltages must accordingly be adjusted to restore the image contrast obtained with the usual filtration of 2.5 mm Al.

(iii) Pseudo-K-edge filters like yttrium, niobium and molybdenum are by no means superior to Fe or Cu filters; they are a bad choice, however, if used alone or in addition to a too small amount of basic filtration due to their transparency for very soft x-rays.

(iv) Dose reductions should be reported primarily in terms of integral dose instead of entrance exposure. The increased backscatter fractions for harder beams must be taken into account. The potential for dose reductions (typically 20%, up to 30%) is smaller than the numbers usually reported.

(v) Added filtration inevitably requires a higher tube load. This is tolerable only if enough system power is available in order to maintain exposure times being appropriate for a given task.

As a more general conclusion we like to point out that filter optimisation in diagnostic radiology should be regarded as a task of considerable complexity which can be managed successfully only by computer assistance based on a solid theoretical background. In accordance with Jennings (1988), however, there should be enough evidence now to put the search for the optimal filter in general diagnostic radiology to rest.

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Résumé

Comparaison des performances des filtres conventionnels et des filtres de raie K utilisés dans les applications générales du radiodiagnostic.

Les auteurs ont étudié les performances des filtres conventionnels et des filtres de raie K pour tout le domaine d'application du radiognostic. Ce problème de l'optimisation des contraintes contradictoires se rapportant à la dose délivrée au patient, au contraste de l'image et au temps d'exposition a été abordé à l'origine par une simulation sur ordinateur. Par comparaison aux filtres conventionnels en acier ou en cuivre, aucun avantage significatif ne peut être obtenu en pratique avec les filtres de raie K, excepté dans les conditions particulières de la fluoroscopie automatique. Les auteurs discutent le choix optimal des filtres conventionnels. Ils décrivent les influences différentes du rayonnement rétrodiffusé sur la dose à la peau et sur la dose intégrale, et insistent sur la nécessité d'apporter une correction pour l'accroissement du rayonnement rétrodiffusé résultant d'une filtration additionnelle. Les réductions potentielles de dose obtenues par une filtration additionnelle ont été trouvées significativement plus faibles que les valeurs généralement rapportées. En définitive, les auteurs font ressortir un certain nombre de problèmes de méthodologie, associés aux études de ce type.

Zusammenfassung

Vergleich der Leistungsmerkmale von konventionellen und K-Kanten-Filtern in der allgemeinen Röntgendiagnostik.

Die Leistungsmerkmale von konventionellen und K-Kanten-Filtern wurden für das gesamte Feld der allgemeinen Röntgendiagnostik untersucht. Das Problem, die widersprüchlichen Erfordernisse von Patiententendosis, Bildkontrast und Aufnahmezeit zu optimieren, wurde vorzugsweise mittels Computer-Simulation behandelt. Im Vergleich zu konventionellen Filtermaterialien wie Eisen oder Kupfer erzielt man mit K-Kantenfiltern—abgesehen von den besonderen Umständen bei automatischer Durchleuchtung—in der Praxis keine signifikanten Vorteile. Die optimale Wahl für konventionelle Filter wird diskutiert. Die unterschiedliche Bedeutung rückgestreuter Strahlung für Haut- und Integraldosis wird demonstriert und die Notwendigkeit, die erhöhte Rückstreuung infolge zusätzlicher Filterung entsprechend zu korrigieren, betont. Das Potential für Dosiseinsparungen durch Hinzufügen von Filterung stellt sich als erheblich kleiner heraus, als es nach den zumeist veröffentlichten Zahlen erscheint. Abschließend wird auf einige Probleme im Hinblick auf die Untersuchungsmethodik besonders eingegangen.

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