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Electron Spectra and the RBE of X Rays

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For an assessment of the possible difference in effectiveness between mammography X rays and conventional X rays, the energy and LET spectra of the released electrons are examined. At photon energies below 20 keV and above 100 keV, the energy of the electrons increases with increasing photon energy, which implies that higher-energy photons produce less densely ionizing radiation and are therefore somewhat less effective per unit dose. However, in the intermediate energy range from 20 keV to 100 keV—the range that is relevant to medical diagnostics—the change from the photoelectric effect to the Compton effect causes a transient decrease of electron energies. The ionization density is therefore similar for 200 kVp X rays and 30 kVp mammography X rays, and the distributions of dose in LET suggest an RBE of 30 kVp mammography X rays compared to 200 kVp X rays of up to 1.3. This is in line with an earlier assessment by Brenner and Amols in terms of microdosimetric data, but it is strongly at variance with a recent claim that X rays for mammography are about four times more effective at small doses than conventional X rays and that they cause a correspondingly greater risk for breast cancer. Since LET need not be the only relevant factor, general response functions are examined here that specify—at low dose—the effect per electron of initial energy *E* and account, for example, for a particular role of the electron range. It is shown that, with any response per electron track that is a nondecreasing function of its starting energy, the low-dose RBE of the mammography X rays relative to the 200 kVp X rays must be substantially less than 2. The Auger electron that accompanies most photoelectrons, but only a minority of the Compton electrons, may increase the effectiveness of the mammography X rays somewhat, but it cannot explain the reported high values of the RBE.

INTRODUCTION

In radiation protection, a familiar distinction is made between low-LET and high-LET radiation. For regulatory purposes, all X rays and γ rays are counted as low-LET radiation. This is reflected in the fact that the radiation weighting factor, w_R, for the effective dose is currently assigned the value 1 for photons and electrons regardless of their energies, and that the quality factor, $Q(L)$, i.e. the weighting factor for the operational quantities ambient dose equivalent and personal dose equivalent, is likewise set equal to 1 for all values of LET that occur with electrons (*1*).

Giving all photon exposures the same weight is a matter of practicality in radiation protection with regard to the setting of exposure limits and to the measurements that are performed to show compliance with these limits, it does not imply that risk estimates are the same for all photon energies. There have in fact been numerous investigations of the biological effect of photons of different energies. Certain radiobiological studies, especially investigations of chromosome aberrations (*2–6*), have provided evidence that X rays can be substantially more effective at low doses than γ rays, and that very soft photons (<10 keV) are in turn more effective than conventional X rays (e.g. 200 kVp X rays).

The issue is relevant, because risk estimates for late effects in humans are based largely on the data from the A-bomb survivors, who were exposed to hard γ rays. Because these risk estimates are derived from observations at fairly large doses, such as 1 Gy or more, there is little reason to assume a substantial difference relative to X rays. However, there could be a difference at low doses. For example, the dose and dose-rate effectiveness factor, DDREF, of 2 that ICRP has postulated (*1*) might possibly apply to γ rays but not to X rays (*7*).

There is, on the other hand, no epidemiological evidence at present for a greater effectiveness of X rays compared to γ rays. On the contrary, the risk estimates from medical cohorts exposed to X rays tend to be, on the whole, somewhat lower than the risk estimates from the A-bomb survivors (*8–10*). It is therefore still an unresolved question whether X rays are associated with higher risk than γ rays.

However, the discussion of the effectiveness of X rays of different energies was recently revived when it was claimed that the comparatively soft X rays used for mammography are substantially more likely than conventional X rays to enhance breast cancer rates. With reference to

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their cell transformation studies with 29 kVp X rays (tungsten anode, 50-μm rhodium filter), Frankenberg *et al.* (*11*, *12*) have asserted that mammography X rays are about eight times more effective per unit absorbed dose in inducing mammary tumors than γ rays and about four times more effective than 200 kVp X rays. This exceeds by far the RBE of about 1.3 which Brenner and Amols (*13*) have inferred from microdosimetric data (*14*) for the similar 28 kVp mammography X rays (molybdenum anode, 30-μm molybdenum filter) relative to orthovoltage X rays, and it has caused major concern with regard to breast cancer screening.

This article is not directed at an assessment of the cell transformation studies of Frankenberg *et al.* and other experimental evidence for or against an increased efficiency of 30 kVp X rays, nor will it deal with the issue of whether the results of cell transformation studies or of cell killing studies are meaningful predictors of radiogenic cancer risks. Instead, the aim is an analysis of the electron spectra and their mean values that can give guidance on the possible differences in effectiveness between mammography X rays and orthovoltage X rays.

The reported high RBE and the postulated high risk factor for mammography X rays were put forward by Frankenberg *et al.* as being in line with a much softer electron spectrum of this radiation, i.e. with an assumed preponderance of 1 keV to 4 keV electrons (*11*). Data from ICRU Report 16 on LET (*15*) were offered (*11*) to support this claim, and these data did indeed seem to show that even 50 kVp X rays are much more densely ionizing than the standard 200 kVp X rays (*16*). Likewise, a study by Sasaki *et al.* on dicentric chromosomes in human lymphocytes (*5*) was quoted [ref. (*12*), Table 3], because it provided an RBE of 8.6 for 50 kVp X rays relative to ^{60}Co γ rays. However, both references were misleading, because it was not pointed out that the ''50 kVp X rays'' in these two instances were extremely soft X rays from a tungsten anode tube with only its inherent filtration. The spectrum of such radiations (*17*) lies—as seen from Fig. 7 in ICRU Report 16—substantially below even the energy spectrum of tritium β particles with its low weighted mean energy of 8.5 keV, while the corresponding energy for the filtered mammography X rays is close to 20 keV (see Appendix 1, Fig. A1). The references to the ''50 kVp X rays'' thus were misguided and were irrelevant to the comparison between mammography X rays and 200 kVp X rays.

The subsequent computations are focused on 30 kVp mammography X rays and 200 kVp X rays, but mean values of electron energy and of LET are also given for monoenergetic photons. A systematic survey of electron spectra and LET distributions for monoenergetic photons is not required for the specific comparison at hand and therefore is not part of the present article.

In the analysis, it will be seen that, while mammography X rays produce an electron spectrum much narrower in energy than the spectrum from orthovoltage X rays, there is little overall difference in ionization density. It is concluded that there is no explanation in terms of LET for mammography X rays being markedly more effective than 200 kVp X rays. On the other hand, it is notable that at equal dose, the mammography X rays release about six times as many electrons with initial energy around 20 keV (see subsequent Fig. 2). Intuitively, this might be taken to explain a high RBE of the 30 kVp X rays, if—perhaps because their range is comparable to that of the cell nucleus—these electrons were particularly effective. However, the relevant parameter is not the number of electrons with a critical *initial* energy, but rather the number of electrons per unit dose with *at least* this energy. This latter number, which is proportional to the electron fluence at the critical energy, will be seen to differ by not more than a factor of 2 for the two types of radiation. Thus it is concluded that whatever effect electrons of specified energy may have, the RBE of the mammography X rays relative to the 200 kVp X rays will be less than 2.

There is one difference between the two types of radiation that is somewhat difficult to quantify. It arises because almost all of the photoelectrons, but only 20% of the Compton electrons, are associated (in water) with a 0.5 keV Auger electron from oxygen. This can make the photoelectrons somewhat more effective than the Compton electrons of the same total energy. In terms of LET, the effect is accounted for, and it is not large. The implication of the spatial association of the Auger electron and the photoelectron is more difficult to assess, but, as will be argued, the impact on the RBE is unlikely to be major.

CONCEPTS AND METHODS

Details of the Computations

Electron spectra and LET data for different types of X rays have been computed variously (*17–23*). Lea's monograph (*22*) contains a compilation of basic data that is still valid. The report on LET by the ICRU (*15*) remains a useful general reference. For his analysis of various radiobiological investigations, Blohm[2] derived extensive information on electron spectra and LET distributions for various types of radiation, including the result that filtered 30 kVp and 150 kVp X rays are not greatly different in LET. There is little need in the subsequent analysis to refer to restricted LET, but where this concept is invoked, reference can be made to Blohm's work, which established the relationship between the mean values of the restricted and unrestricted LET.

The energy or LET spectra of the electrons released by energetic photons do not depend in a simple way on the photon energy. The energy of the photoelectrons is roughly equal to the energy of the photons. The mean energy of the Compton electrons, while being substantially smaller, likewise increases with the photon energy. At low photon energies ($<$20 keV) and at high energies ($>$100 keV), i.e. at energies where one of the two effects dominates (see Fig. 1, upper panel), the electron energy is thus strongly correlated with the photon energy; i.e., higher photon energies correspond to lower values of LET. However, in the intermediate region of photon energies between 20 keV and 100 keV, the trend is

[2] R. Blohm, Durchgang von Elektronen durch strahlenempfindliche Bereiche des Zellkerns. Dissertation, Georg-August-Universität Göttingen, 1983.

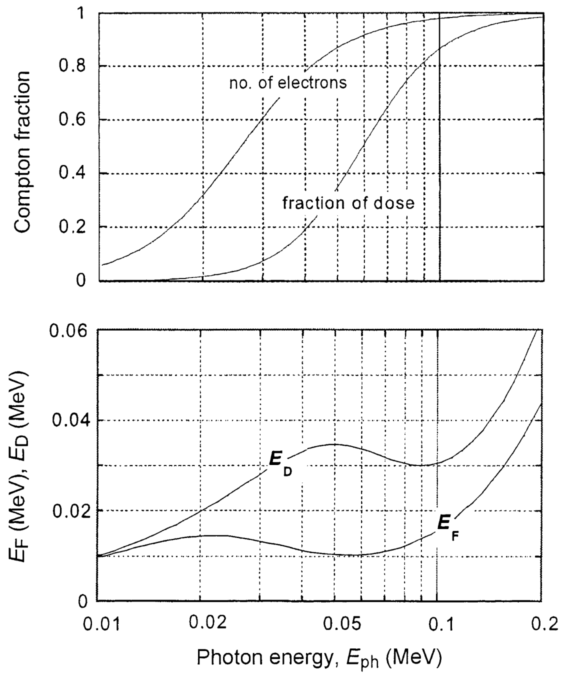

FIG. 1. Upper panel: The fraction of Compton electrons among all electrons released by photons of the specified energy (upper curve) and the fraction of the dose contributed by the Compton electrons (lower curve). Lower panel: The frequency average, E_F, and the dose average, E_D, of the initial energy of electrons released by photons of specified energy. The photoelectrons and their associated 0.5 keV Auger electrons are counted as one track.

reversed and, over a certain energy range, the mean electron energy decreases with increasing photon energy (see Fig. 1, lower panel). The reason for this photon–electron anomaly is the gradual transition from the photoelectrons to the less energetic Compton electrons. The consequence is that the average ionization density is roughly the same for the different types of X rays used in medical diagnostics.

The computations are performed for water as a substitute for tissue. The unrestricted stopping power is computed for a mean excitation energy $I = 75$ eV. The monograph by Kase *et al.* (*23*) is a convenient reference to the energy and angular dependent Klein-Nishina Compton cross sections [their Eq. (7.15)]. The photoeffect cross section is taken to be equal to the total Compton cross section at a photon energy of 26 keV and to decrease with the third power of the photon energy.

The photoelectric effect by a photon of energy E_{ph} is treated as always giving rise to an electron with kinetic energy ($E_{ph} - 0.5$ keV) coupled at its starting point with the 0.5 keV Auger electron from oxygen. Since there are two K-shell electrons among the electrons of the water molecule, the effect takes place only with 20% of the Compton electrons. The combined track can be somewhat more effective than the track of a single electron of the same total energy. However, the difference is not likely to be large, because the 0.5 keV "track ends", as seen in Table 1, are not infrequent in the slowing-down pattern of 10 keV or 20 keV electrons. At 10 keV, a photoelectron contains due to the Auger effect on average only 23% more 0.5 keV track ends than a Compton electron; at 20 keV, the difference is merely 13%.

The collision stopping power of the electrons is computed according to ICRU 37 [Eq. (2.16) in ref. (*25*)]. The resulting numerical values agree with those given in ICRU 16 (*15*). All spectra are derived for the first collisions only, i.e. for the undegraded photons of specified energy E_{ph}. The results are therefore representative for small exposed objects. For larger objects, differences in radiation quality will be somewhat less between different photon energies.

The Notion of the Response Functions that Determine the Low-Dose RBE

Certain relevant quantities and concepts will be defined before numerical data for 30 kVp and 200 kVp X rays are given and are analyzed. Since it is felt desirable to detach the conceptual subtleties of the dose quantities (*26*) from the present numerical investigation, the term dose will be employed somewhat loosely. It can be understood as kerma or as mean absorbed dose in a reference volume that is sufficiently small to experience not more than one interaction per photon but is large enough, on the other hand, to contain the electron tracks. With electron energies up to about 100 keV, this applies to a volume of fractions of a millimeter. In cell studies, where the exposed layer is smaller, steps are usually taken to ensure electron equilibrium.

Let $n(E)\,dE$ be the number per unit energy absorbed of primary electrons released with energy E to $(E + dE)$ within the reference volume. Furthermore, let $\rho(E)$ be the average effect contribution, at low dose, of an electron with starting energy E. Under the low-dose condition of independent action of the primary electrons, the total response per unit energy absorbed is then

$$R = \int \rho(E)\, n(E)\, dE. \tag{1}$$

The low-dose condition of independent additive action is a postulate rather than a demonstrable fact. A typical two-view mammography exposure amounts to about 4 mGy. At this dose, a cell will be traversed by several electrons. In principle, there could be nonlinearity even at these low doses, and in view of potential complexities such as the bystander effect, there is no way to exclude with absolute certainty nonlinear relationships even at lower doses. However, linearity is the widely assumed low-dose condition in quantitative risk modeling, and there is no conclusive epidemiological evidence against this assumption.

The response, R, and the response function, $\rho(E)$, per electron relate

TABLE 1
Mean Number of 0.5 keV Track Ends per Photoelectron and Compton Electron

	Multiplication factor, $F_{0.5keV}$	Auger electrons (from photon)	Total 0.5 keV track ends	Ratio photo/Compton
10 keV photoelectron	2.7	1	3.7	1.23
Compton electron	2.8	0.2	3.0	
20 keV photoelectron	4.9	1	5.9	1.13
Compton electron	5.0	0.2	5.2	

Notes. The multiplication factor $F_{0.5keV}$ specifies the number of 0.5 keV track ends in the slowing-down pattern of the electrons of specified initial energy, the track end of the primary electron itself being included. The numbers are derived from ref. (*24*) and footnote 2 (see p. 14) and have been confirmed through Monte Carlo calculations (Dr. Chen Jing, private communication). The energies $E = 10$ keV and 20 keV include the Auger electrons.

to a specified end point and to specified exposure circumstances.[3] The numerical values of $\rho(E)$ generally will not be known, but the essential point is that, under the low-dose condition, there must be a certain dependence, $\rho(E)$, that applies equally with X rays or γ rays of all energies. The low-dose RBE of the two types of X rays is then equal to the ratio of the response parameters R_{30kV} and R_{200kV} for the two types of radiation:

$$\mathrm{RBE}_{30kV/}R_{200kV} = R_{30kV/rb}/R_{200kV} \qquad (2)$$
$$= \int \rho(E)\, n_{30kV}(E)\, dE \Big/ \int \rho(E)\, n_{200kV}(E)\, dE.$$

It follows from this equation that the normalization of $\rho(E)$ is irrelevant, and in the subsequent computations no attention will therefore be given to a scaling factor.

$\rho(E)$ can be taken to be a non-decreasing function of E, which reflects the assumption that, say, a 30 keV electron will produce no less—and, in fact more—effect than a 20 keV electron. The assumption may appear trivial, since a 30 keV electron track ''contains'' a 20 keV track, which results by cutting off the initial segment where the 30 keV electron is slowed down to 20 keV. In spite of being nearly obvious, the condition is spelled out here, because it is essential for the rigor of the subsequent arguments. Exceptional models might violate the assumption, but they are not of sufficient generality to require consideration in the present context.

Equation (2) allows certain firm conclusions about the low-dose RBE of two types of photon or electron radiations. Thus, if the low-dose RBE of mammography X rays relative to 200 kVp X rays is to be 4, the integral must be four times larger for the mammography X rays than for 200 kVp X rays. Once the distributions $n(E)$ are known for either radiation, it can be determined whether a $\rho(E)$ exists that meets the condition. The data in the subsequent section will show that there can be no such function. In fact, it will be recognized that with any reasonable response function, the two kinds of radiation will differ only moderately in their effectiveness.

To seek a *monotonous* response function $\rho(E)$ that maximizes the ratio of two integrals is more difficult than seeking a *non-negative* function with this property. It is therefore convenient to change Eq. (1) so that it contains the non-negative derivative, $r(E)$, of $\rho(E)$. This can be done by partial integration which provides

$$R = \int r(E)\, N(E)\, dE, \qquad (3)$$

with $r(E) = d\rho(E)/dE$ and $N(E) = \int_E^\infty n(E)\, dE'$. $N(E)$ is the number of primary electrons released with energy $>E$ per unit energy absorbed. $r(E)\, dE$ is the (average) increment (per electron track) of the response, as the electron energy increases from E to $(E + dE)$. In this sense, it can be called the *response per unit energy absorbed* at instantaneous electron energy E. This is a helpful notion that has been used in familiar models by postulating, for example, that $r(E)$ is proportional to the restricted LET L_Δ (*27*).[2] However, for the subsequent considerations, it is important to note that $r(E)$ is not bound to any such interpretation. Being defined as the derivative of $\rho(E)$, it is not linked to a particular model. The concept requires merely the independent action of individual primary electron tracks, which is, as stated, a principal assumption at low dose.

NUMERICAL RESULTS

Energy and LET Spectra

Figure 2 gives the number, $E\, n(E)$, of electrons per unit log interval of initial energy, E, for 30 kVp mammography

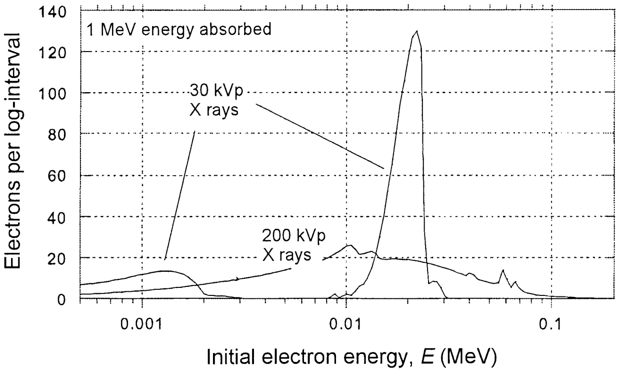

FIG. 2. The number, $E\, n(E)$, of primary electrons with initial energy, E, per log interval of E. The numbers are given for 1 MeV energy absorbed. The distribution for the 30 kVp X rays consists of two separate parts that represent the minor contribution of Compton electrons and the major contribution of photoelectrons. The Auger electrons are included in E.

X rays (tungsten anode, 50-μm rhodium filter) and for conventional 200 kVp X rays (tungsten anode, 1-mm copper and 2-mm aluminum filter; see the Appendix). The numbers relate to 1 MeV energy absorbed (which corresponds to 10 mGy in a tissue cube with a side length of 25 μm).

The frequency and dose averages, E_F and E_D, are given in Table 2, together with the data for the somewhat different 30 kVp X rays from a molybdenum anode (30-μm molybdenum filter) and 200 kVp X rays (tungsten anode) with weaker filtration (0.5 mm copper). Unless otherwise specified, all diagrams and numerical values in this paper refer to the 30 kVp X rays from the tungsten anode and the 200 kVp X rays with the stronger filtration.

The mammography X rays release predominantly photoelectrons, and their energy spectrum is nearly equal to the energy spectrum of the photons (see the Appendix). In contrast, the 200 kVp X rays release mostly Compton electrons, and the resulting energy spectrum is broad. In the narrow spectrum of the mammography X rays, there are substantially more electrons with starting energies around 15 keV to 20 keV, which might suggest a particularly high effectiveness of these electrons as explanation of the presumed high RBE of this radiation. This assumption has indeed been made; i.e., it has been argued that electrons of about 15 keV are particularly effective, because their range is sufficient to traverse the cell nucleus and thus to cause lesions in separate chromosomes (*12, 27*). The subsequent considerations will examine this postulate but will lead to the conclusion that it fails to explain the presumed high RBE of mammography X rays.

Before dealing with the more general approach, it is helpful to consider the familiar treatment in terms of LET. In this treatment, a weighting function is used that depends on restricted or unrestricted LET. Without loss of generality, one can consider the case of the unrestricted LET (see Appendix 2); the low-dose RBE is then expressed as

[3] $\rho(E)$, the response per primary electron of energy E, is dimensionless and will be treated as such even where it is, in the subsequent section, expressed in terms of LET and energy E.

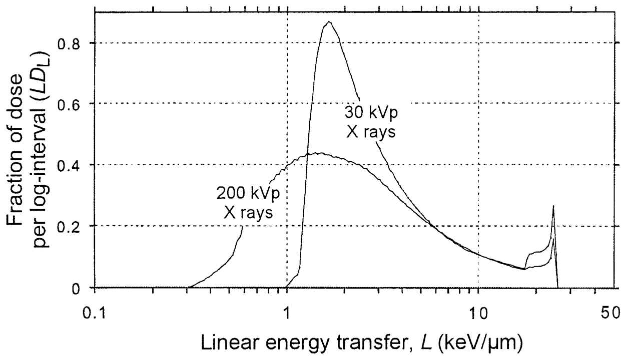

FIG. 3. The distribution of dose in unrestricted linear energy transfer, L, for the 30 kVp X rays and the 200 kVp X rays. The frequency and the dose mean values are 2.4 keV/μm and 4.3 keV/μm for the 30 kVp X rays and 1.55 keV/μm and 3.5 keV/μm for the 200 kVp X rays.

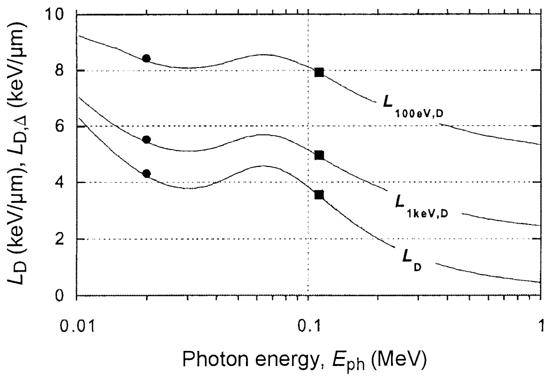

FIG. 4. The dose mean restricted and unrestricted linear energy transfer for the electrons liberated by monoenergetic photons of energy E_{ph}. The dots and squares give the values for the 30 kVp and the 200 kVp X rays. They are plotted at the weighted photon energies of the X ray spectra (Table A1, Appendix).

$$\mathrm{RBE} = \int r(L) D_{L;30\mathrm{kV}}\, \mathrm{d}L \Big/ \int r(L)\, D_{L;200\mathrm{kV}}\, \mathrm{d}L, \quad (4)$$

where D_L is the normalized distribution of dose in L; i.e., D_L dL is the fraction of the dose delivered at linear energy transfer L to L + dL.

The response function $r(L)$ is analogous to the function $r(E)$ in Eq. (3). It is also analogous to the function $r(y)$ used by Brenner and Amols (*13*) in their analysis of the RBE of mammography X rays and is also analogous to the quality factor $Q(L)$ in radiation protection.

Figure 3 gives the distribution, D_L, of dose in LET for the 30 kVp mammography X rays and the 200 kVp X rays. There is a substantial difference between the two distributions. However, the ratio of the dose contributions does not exceed 2 at any of the LET values; this implies that no weighting function $r(L)$ can make the ratio of the integrals in Eq. (4) larger than 2. The LET spectra differ even less, especially at the high LET values, if they are expressed in terms of restricted LET. It follows that there can be no LET model that explains an RBE of the 30 kVp X rays relative to the 200 kVp X rays in excess of 2. In fact, any plausible response function will provide an RBE less than 1.5.

A number of authors have come to the conclusion that the effectiveness of a radiation is proportional to its dose-averaged linear energy transfer, which implies that the response function is simply proportional to LET. Blohm[2] has argued, on the basis of various experimental data from chromosome and mutation studies, that the relevant δ-ray cutoff is Δ = 100 eV. More recently, larger cutoff values of 500 eV or 1 keV have been assumed (*27*).

Figure 4 gives the dose-averaged LET values for the first-generation electron spectra released by monoenergetic photons. The values of $L_{\Delta,D}$ are obtained in terms of a relationship between L_D and $L_{\Delta,D}$ that applies, according to the results derived by Blohm,[2] to all different types of photon and electron radiations that were investigated (see the Appendix).

The results for the 30 kVp and the 200 kVp X rays are superimposed on the curves as dots and squares. Plotted at the weighted photon energies of the X-ray spectra (see Table A1, Appendix), they agree very nearly with the values for the monoenergetic photons.

The present considerations are aimed at exploring the largest possible RBE values of the mammography X rays that might result from the LET models. Therefore, Table 3 lists only the values with regard to unrestricted LET. The RBE values then range up to 1.3 for the 30 kVp X rays from molybdenum, which is in line with the RBE of 1.3 for the 30 kVp mammography X rays relative to 200 kVp X rays that Brenner and Amols (*13*) have obtained in their analysis in terms of microdosimetric measurements by Dvorak and Kliauga (*14*).

An Upper Limit for the RBE Inferred from the Energy Spectra of the Electrons

In the usual models, low-energy electrons are more effective per unit energy because of their somewhat higher LET. The increased effectiveness is a matter of local energy density; the range of the electrons does not enter the model. Since LET cannot explain the assumed higher RBE of the mammography X rays, more complicated response functions need to be examined that increase with increasing

TABLE 2
Energy and Frequency Mean of the Initial Energy of the Electrons Released by 30 kVp and 200 kVp X Rays

X rays	E_F (keV)	E_D (keV)
30 kVp		
Tungsten, 50 μm rhodium filter	14.0	19.6
Molybdenum 30-μm molybdenum filter	13.4	17.5
200 kVp		
Tungsten, 1 mm copper, 2 mm aluminum	16.5	36.3
Tungsten, 0.5 mm copper	15.1	34.6

Note. A photoelectron jointly with its associated Auger electron is counted as one event.

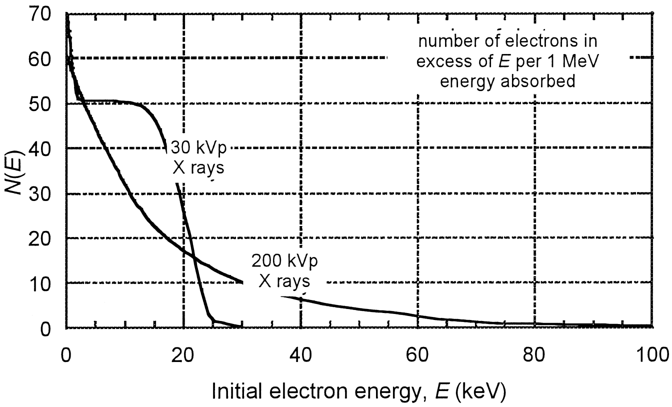

FIG. 5. Number, $N(E)$, of primary electrons with initial energy in excess of E. As with $n(E)$ in Fig. 2, the numbers are given for 1 MeV absorbed energy. The 0.5 keV Auger electrons are treated as part of the track of the photoelectron.

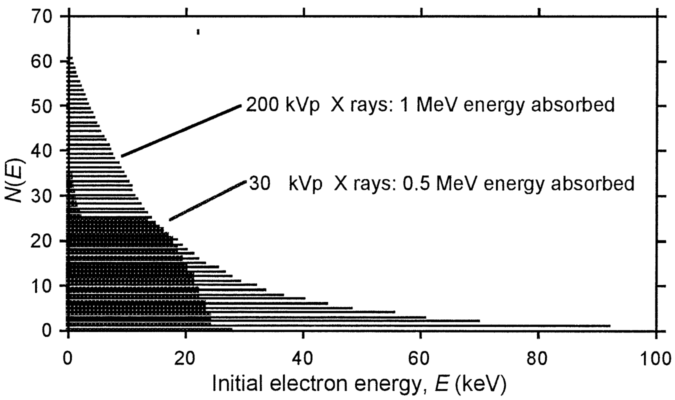

FIG. 6. Number, $N(E)$, of primary electrons with initial energy in excess of the specified energy, E. Each horizontal line represents an electron with an energy indicated by its length. Sixty-one electrons from the 200 kVp X rays correspond to 1 MeV energy absorbed. Thirty-six electrons from the 30 kVp X rays correspond to 0.5 MeV energy absorbed. The tracks from the 30 kVp X rays are contained within those from the 200 kVp X rays; i.e., a dose from 30 kVp X rays must have less effect than twice this dose from 200 kVp X rays.

electron energy, or range, in such a way that a particularly high effectiveness is attained at the electron energies of 15 keV or 20 keV which are more prevalent with the mammography X rays. The question of interest is whether there can be a response function that provides the assumed high values, say 3 or 4, of the RBE of mammography X rays relative to 200 kVp X rays. The matter will first be discussed without consideration of the Auger effect; i.e., a Compton electron and a photoelectron of the same energy (including the 0.5 keV Auger electron) will be considered as equivalent at this point. The potential impact of the Auger effect needs to be considered separately, but, as has been explained in terms of Table 1, it is not likely to be major.

The analysis could refer to Eq. (2) and the (monotonous) response function $\rho(E)$. But, as stated, the search for a suitable response function is made more transparent by the equivalent Eq. (3) and the (non-negative) derivative, $r(E)$, of the response function. The RBE is then given by

$$\begin{aligned}\mathrm{RBE}_{30\mathrm{kV}/200\mathrm{kV}} &= R_{30\mathrm{kV}}/R_{200\mathrm{kV}} \\ &= \int r(E)\, N_{30\mathrm{kV}}(E)\, \mathrm{d}E \Big/ \int r(E)\, N_{200\mathrm{kV}}(E)\, \mathrm{d}E. \qquad (5)\end{aligned}$$

Figure 5 gives the functions $N(E)$ for the 30 kVp mammography X rays and the 200 kVp X rays. Their ratio reaches its largest value of about 2 near 15 keV, and it follows from Eq. (5) that no response function can provide an RBE in excess of 2.

Blohm (Fig. 3 in footnote 2) presented analogous curves for the 30 kVp X rays from a molybdenum anode (30-μm molybdenum filter) and 150 kVp X rays (tungsten anode, 0.7-mm copper filter). In this case, the maximum ratio of the electron numbers $N(E)$ was apparently about 1.7, and it occurred between 10 keV and 15 keV.

Data analogous to those in Fig. 5 can also be given in terms of all electrons, including secondaries (δ rays). In principle, this could constrain the maximum value of the RBE further. However, the difference is insubstantial, because there are no 15 keV secondaries in the case of 30 kVp X rays and there are too few in the case of 200 kVp X rays to make a difference (*24*).[2]

The preceding considerations have provided a general proof, with a minimum of model assumptions, that the low-dose RBE of 30 kVp X rays relative to 200 kVp X rays is bound to be less than 2. Figure 6 does not add to the argument, but it illustrates it in terms of a modified graph. The primary electrons are represented here by horizontal lines with lengths proportional to energies. The distribution $N(E)$ for the 200 kVp X rays is indicated by 61 electrons released per 1 MeV energy absorbed (mean electron energy 16.5 keV). For the 30 kVp X rays, 36 shorter lines—drawn between those for the 200 kVp X rays—represent the electrons released per 0.5 MeV (mean electron energy 14 keV). If the RBE of the 30 kVp X rays relative to the 200 kVp X rays were 2, the two sets of electrons would have to produce the same effect.

The diagram demonstrates that the electron tracks from a dose D of the 30 kVp X rays are a subset of the tracks from a dose $2D$ of the 200 kVp X rays. Each of the tracks for the 30 kVp X rays is paired in the diagram with an electron of at least the same energy from the 200 kVp radiation, i.e. with an electron track that ‘‘contains’’ it. In this association, half of the energy of the tracks for the 200 kVp X rays remains unmatched. Unless this energy is without effect, the RBE of the 30 kVp X rays cannot be equal to 2. The conclusion disregards the difference between photoelectrons and Compton electrons that is due to the Auger effect, but it is otherwise rigorous.

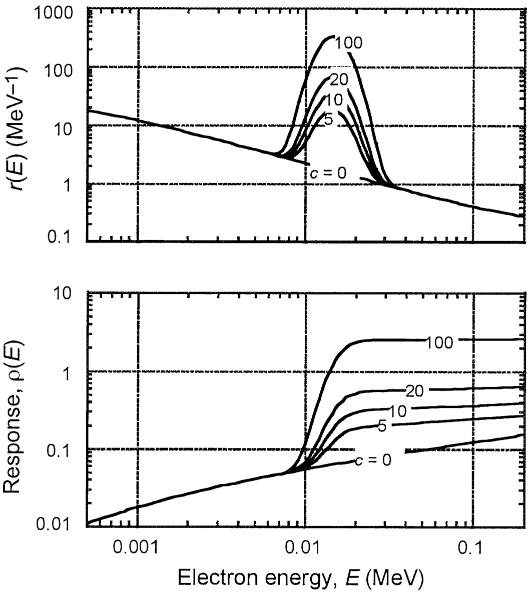

FIG. 7. Upper panel: The response function $r(E)$, i.e. the derivative of the response $r(E)$, per electron. The lowest curve ($c = 0$) corresponds to the linear energy transfer L. The parameter c represents the hypothetical increase of efficiency as the electron approaches the putative critical energy of about 15 keV. Even the extreme assumption of $c = 100$ corresponds to an RBE of the 30 kVp relative to the 200 kVp X rays of only about 1.7 (see Table 3). Lower panel: The response functions $\rho(E)$, i.e. the integrals of $r(E)$. They represent the effect per electron of specified initial energy, E.

The RBE Resulting with Putative Response Functions

The strength of the argument in the preceding section lies in its generality, i.e. its independence from any model assumption, apart from the low-dose condition of the independent additive action of the primary electrons. However, the somewhat abstract nature of the reasoning could be seen as a drawback. It is therefore helpful to explore the issue numerically in terms of hypothetical response functions that might apply if there were, for example, a critical dependence on electron range (*11*, *27*). These considerations will serve to demonstrate that even with very special response functions, the RBE of 30 kVp X rays relative to 200 kVp X rays is bound to be substantially less than 2.

In the LET model, the largest RBE of mammography X rays is attained if reference is made to *unrestricted* LET (see Fig. 4). One may therefore start out by equating $r(E)$ with $L(E)$ and then examine a modification that represents a putatively increased efficiency of the electrons at energies around 15 keV, i.e. of electrons with a range of a few micrometers. On the assumption of a step function being unrealistic, $r(E)$ can be modified in terms of a narrow Gaussian, $G[\ln(E);\sigma]$, centered at 15 keV and superimposed on the LET dependence:

$$r(E) = L(E)\ [1 + c\ G(\ln(E);\sigma)]. \tag{6}$$

The dependencies in Eq. (6) are represented in the upper panel of Fig. 7 for $\sigma = 0.2$, i.e. for a reasonably narrow peak, and for various values of the coefficient c that determines the magnitude of the modifying term. Table 4 gives the resulting values of R and the corresponding RBE of the mammography X rays relative to the 200 kVp X rays. The RBE increases as larger values of c are chosen, but, in agreement with the earlier more general argument, it never reaches 2.

The lower panel of Fig. 7 gives the integrals of $r(E)$, i.e. the corresponding response functions $\rho(E)$. Since the response per electron, $\rho(E)$, has a more tangible meaning than its derivative, $r(E)$, it makes it easier to judge the magnitude of c that might make sense in terms of radiobiology. The parameter $c = 5$ corresponds—as judged from the lower panel in Fig. 7—to roughly a threefold increase in effectiveness for a 15 keV electron, which might still be a ten-

TABLE 4
Response Parameters, *R*, for 30 kVp and 200 kVp X Rays and the Corresponding *RBE* of the 30 kVp to the 200 kVp X Rays

c	0	5	10	20	100
R_{30kV}	4.34	9.37	14.33	24.27	103.7
R_{200kV}	3.50	6.21	8.97	14.49	58.6
$RBE_{30kV/200kV}$	1.24	1.51	1.60	1.67	1.77

Note. The values are given in dependence on the coefficient c that represents the magnitude of the assumed increase of the response at electron energies around 15 keV (see Fig. 7).

TABLE 3
The Frequency and Dose-Weighted Linear Energy Transfer, L_F and L_D, for 30 kVp and for 200 kVp X Rays, and the *RBE* Values that would Apply, if the Effectiveness of the Radiation were Proportional to L_D

X rays	L_F/keV (μm)	L_D/keV (μm)	RBE
30 kVp			
Tungsten, 50 μm rhodium	2.44 (2.35)	4.34 (3.90)	1.21
Molybdenum, 30 μm molybdenum	2.68 (2.57)	4.65 (4.13)	1.30
200 kVp			1
Tungsten, 1 mm copper, 2 mm aluminum	1.56 (1.54)	3.58 (3.48)	
Tungsten, 0.5 mm copper	1.61 (1.61)	3.74 (3.62)	1.04

Note. The numbers in parentheses result if the photon induced Auger effect is disregarded.

able assumption.[4] The RBE of the 30 kVp X rays would then be 1.5. Higher values of *c* correspond to increases that appear unrealistic. It follows that a credible response function might lead to an RBE of the mammography X rays relative to 200 kVp X rays of about 1.5, but hardly to a larger value.

CONCLUSION

The spectra of electrons released by 30 kVp mammography X rays and by moderately filtered 200 kVp X rays do not appear to permit a response function that can explain an RBE of the mammography X rays relative to 200 kVp X rays larger than about 1.5. In fact, a value of about 1.3, as deduced by Brenner and Amols (*13*) from microdosimetric data, seems more likely.

As stated, the RBE of the mammography X rays could be enhanced somewhat because of the Auger effect. Since the 0.5 keV Auger electron accompanies (in water) all photoelectrons, but only 20% of the Compton electrons, it increases the dose-averaged linear energy transfer L_D by about 11% for the 30 kVp X rays, but only by about 3% for the 200 kVp X rays. This is taken into account in the LET calculations, but it increases the RBE by only about 8% if unrestricted LET is used as the weighting factor. In models that invoke a δ-ray cutoff, the role of the Auger effect is less. However, the impact of the Auger electron might go beyond the LET effect if 500 eV were a critical energy to deposit within a sensitive target and two targets separated by a few micrometers had to be affected. This could make the possible ‘‘range effect’’ somewhat larger for the photoelectrons than the Compton electrons.

However, as seen in Table 1, the Auger effect does not increase the number of 0.5 keV track ends greatly. If, beyond the LET effect, the effectiveness of the electrons were to increase in proportion to the number of 0.5 keV track ends—probably a very conservative assumption—the Auger effect might account for an increase in the RBE by perhaps 20%. While its potential impact is undoubtedly of interest, the Auger effect is thus unlikely to be a major factor.

In experimental studies, for example on chromosome aberrations or cell transformation, there can be some features that enhance the difference between 30 kVp and conventional X rays. One possible factor is that reference X rays may be chosen that are harder and therefore somewhat less effective than standard 200 kVp X rays. For example, 220 kVp X rays heavily filtered by 2 mm aluminum plus 3.3 mm copper have been used in one of the major studies on chromosome aberrations (*3*). Another possibility is that in some studies, cells are in thin layers without covering material, in which case the soft part of the mammography photon spectrum contributes most strongly. While none of these differences come close to explaining the reported high RBE values for mammography X rays, they may still add up to an appreciable difference. But, apart from not being representative for the comparison of mammography X rays to conventional X rays, the increase is unlikely to be substantial.

Any statement of a large RBE, such as the claim (*11, 12*) of a factor of about 8 between mammography X rays and γ rays, and of a factor of about 4 between mammography X rays and conventional X rays, should thus be viewed with great caution and must call for careful scrutiny of the underlying radiobiological evidence.

[4] There is in fact little radiobiological evidence for a special effectiveness of electrons of about 15 keV. The studies of chromosome aberrations that Sasaki *et al.* (*5*) performed with monoenergetic photons indicate instead some especially high effectiveness at about 6.5 keV. However, for reliable conclusions, the present analysis must not rule out potential response functions, unless they are evidently implausible.

APPENDIX

1. Photon Spectra for Mammography and a Spectrum for Unfiltered 50 kVp X Rays

Figure A1 gives the distribution of dose in photon energy for mammography X rays produced at 30 kVp peak voltage with a tungsten anode and 50-μm rhodium filter (*29*) and for 200 kVp X rays with a tungsten anode and 1-mm copper plus 2-mm aluminum filter.[5] The dose-averaged photon energy is 20 keV for the 30 kVp X rays and 111 keV for the 200 kVp X rays. For the 30 kVp mammography X rays, the added filtration by an anterior 3-mm Perspex plate for fixation of the breast makes the actual dose-averaged photon energy slightly larger (20.5 keV).

With the more penetrating 200 kVp X rays, the dose is taken to be the water kerma free in air. With the much less penetrating 30 keV X rays, it is taken to be the kerma averaged over the absorber. In the case of the mammography X rays, the low-energy part of the spectrum contributes somewhat more strongly—in line with the E_{ph}^{-3} dependence of the photoeffect cross section—to the dose in the surface layer of the exposed medium. The dose-averaged photon energy is then 18.1 keV rather than 20 keV. The ionization density can thus be somewhat larger in cell studies where the 30 kVp X rays expose only a thin cell layer, rather than a tissue which absorbs most of the radiation.

The dashed curve on the left gives the distribution of *exposure rate* in photon energy for the 50 kVp X rays from a tube with tungsten anode and only inherent filtration (a 1-mm beryllium window) as measured by Burke and Pettit [their Fig. 7 (*17*)]. ICRU 16 (*15*) has presented, for these 50 kVp X rays, the distribution of fluence (including δ rays) in electron energy and the sum distribution of dose in L_{100eV}. While the underlying energy spectrum of photons or primary electrons is not specified, it is readily seen from Fig. 7 in ICRU 16 that this spectrum is substantially softer than even the energy spectrum of tritium β particles. It follows that the energy–fluence spectrum underlying the ICRU’s 50 kVp X-ray data must in fact be even lower in energy than the exposure rate distribution measured by Burke and Pettit (Fig. A1, dashed line). This type of minimally filtered 50 kVp X-ray spectrum has been employed with careful dosimetry by Hoshi *et al.* (*29*) for cell inactivation studies and by Sasaki *et al.* (*5*) for the investigation of chromosome aberrations. It is clear that such extremely soft X rays exhibit considerably higher LET and higher efficiency in cell studies than mammography X rays. Any linkage of the ICRP data (*15*) and the RBE (*5*) for the unfiltered 50 kVp X rays to the presumed RBE (*11, 12*) of mammography X rays is thus deceptive.

[5] W. W. Seelentag, W. Panzer, G. Drexler, L. Platz and F. Santner, A Catalogue of Spectra for the Calibration of Dosemeters. GSF Bericht 560, GSF-Forschungszentrum für Umwelt und Gesundheit, 1979.

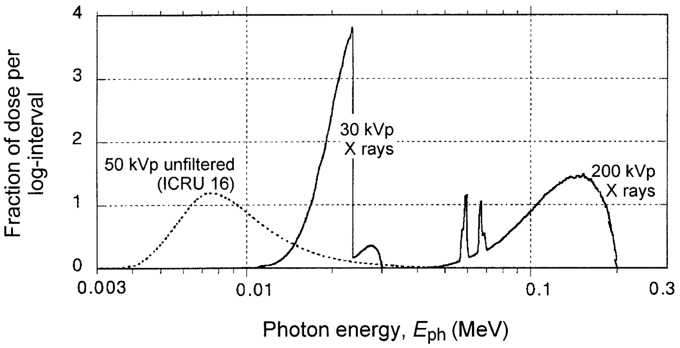

FIG. A1. The distribution of dose in photon energy for 30 kVp mammography X rays (tungsten anode, 50-μm and 60-μm molybdenum filter) (*29*) and for 200 kVp x rays (tungsten anode, 1-mm copper plus 2-mm aluminum filter).[5] The frequency and dose mean photon energies are listed in Table A1. The dashed left curve gives the distribution of *exposure rate* in photon energy for the much softer *unfiltered* 50 kVp X rays which corresponds to the data in ICRU 16 (*15, 16*) and which must not be mistaken as being representative of mammography X rays.

2. Interrelationship between Dose Averages for Restricted and Unrestricted LET

In Table 3, reference has been made to the dose-averaged mean values of restricted linear energy transfer, $L_{\Delta,D}$. These values are derived from the dose-averaged values, L_D, for the 30 kVp and the 200 kVp X rays and from the interrelationships between L_D and $L_{\Delta,D}$ that can be deduced from the data presented by Blohm (his Table III[2]) for various types of photon and electron radiations. While the relationships may not be strictly unique, they do appear to follow a joint dependence (see Fig. A2). These relationships were used to obtain the data in Table 3 and Fig. 4.

When RBE is modeled in terms of LET, reference is usually made to restricted linear energy transfer L_Δ. This is somewhat arbitrary, because, as can be seen from Fig. A2, no distinction can be made, within the accuracy of most experiments, between the response functions

$$r(L_\Delta) = L_\Delta \tag{A1}$$

and:

$$r(L) = \lambda + L, \tag{A2}$$

if λ is set equal to 4 keV/μm for $\Delta = 100$ eV or equal to 2 keV/μm for $\Delta = 1$ keV.

Furthermore, there is no need to consider the formulation in terms of restricted LET that corresponds to Eq. (4). The reason is that any such formulation can be rewritten in terms of L. This is seen from the interrelationship

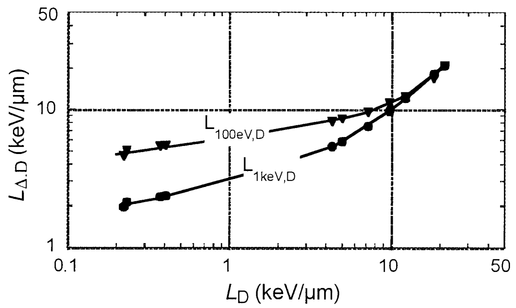

FIG. A2. The dependence of $L_{1keV,D}$ and of $L_{100eV,D}$ on L_D, according to the data computed by Blohm[2] (see p. 14) for a number of radiations (from left: 2.9 MeV electrons, 13 MeV electrons, ^{32}P β particles, ^{60}Co γ rays, 150 kVp X rays, 30 kVp X rays, ^{3}H β particles, 10 kV, 5 kV, 3 kV and 1.5 kV X rays).

TABLE A1
Frequency and Dose Mean Values of the Photon Energy for the 30 kVp and 200 kVp X-Ray Spectra

X rays	$E_{ph,F}$ (keV)	$E_{ph,D}$ (keV)
30 kVp		
Tungsten anode, 50 μm rhodium filter	19.4	20.0
Molybdenum anode, 30 μm molybdenum	17.0	17.7
200 kVp		
Tungsten anode, 1 mm copper + 2 mm aluminum	97.4	110.8
Tungsten anode, 0.5 mm copper	85.2	99.3

$$r(L)\,\mathrm{d}L = \left(\int r'(L_\Delta)\, u(L_\Delta, L)\, \mathrm{d}L_\Delta \right) \mathrm{d}L. \tag{A3}$$

$u(L_\Delta, L)\,\mathrm{d}L$ is the distribution of L_Δ that is due to a primary electron track segment with linear energy transfer L and its δ rays. Equation (A3) is complicated, but it makes the point that for any response function $r'(L_\Delta)$ there is an equivalent response function $r(L)$, so that there is no need, in the present context, to invoke L_Δ.

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