FROM THE NATIONAL INSTITUTE OF RADIATION PROTECTION, S-104 01 STOCKHOLM, SWEDEN.

ACCURACY OF MEGAVOLT RADIATION DOSIMETRY USING THERMOLUMINESCENT LITHIUM FLUORIDE

B.-I. RUDÉN and L. G. BENGTSSON

At Radiumhemmet in Stockholm, lithium fluoride dosemeters are used routinely in radiation therapy (RUDÉN 1971, RUDÉN & NILSSON 1975). As there are facilities to treat patients with ^{60}Co-units, a 6 MV-linear accelerator and a 42 MeV betatron, it is necessary to know the response of the different kinds of LiF dosemeters at different roentgen and electron energies in order to determine the absorbed dose given to the patients.

During the last 12 years many reports have appeared on the energy dependence of LiF dosemeters used with high energy electrons and roentgen rays. PALIWAL & ALMOND (1975) included in their report a table giving some of the authors who have published data on the response of LiF to electrons relative to ^{60}Co γ-radiation. The results seem inconsistent. Some authors found about 10 per cent decrease in the response of LiF to electrons with energies above a few MeV and high energy roentgen radiation relative to ^{60}Co γ-radiation. Others report no significant differences in the response. Attempts have been made in the past to explain these divergent findings in terms of cavity theories (BURLIN et coll. 1969, ALMOND & MCCRAY 1970, TURNER & ANDERSON 1973, PALIWAL & ALMOND, HOLT et coll. 1975).

The purpose of this investigation is to review several factors influencing the dosemeter response by one to ten per cent. These factors are used to explain, at least in part, the experimentally found response of several types of LiF dosemeters.

Supported by grants from the Cancer Society of Stockholm and the King Gustaf V Jubilee Fund.
Submitted for publication 24 May 1976.

Table 1

Atomic composition of LiF dosemeters, along with the isotopic composition of the lithium, mean electron density $\langle Z/A \rangle$ and mean atomic number $\bar{Z}$

Dosemeter	Dimension	Atomic composition, % by weight				$\langle Z/A \rangle$	$\bar{Z}$
		^{6}Li	^{7}Li	F	C		
D-LiF-N-0.13 in teflon (Isotope Inc.)	0.13 mm thick ⌀ 12.0 mm	0.59	7.43	75.17	16.81	0.475	8.03
D-LiF-7-0.13 in teflon (Isotope Inc.)	0.13 mm thick ⌀ 12.7 mm	0.008	8.086	75.096	16.81	0.474	8.03
D-LiF-6-0.13 in teflon (Isotope Inc.)	0.13 mm thick ⌀ 11.7 mm	6.94	0.32	75.93	16.81	0.480	8.02
D-LiF-7-0.4 in teflon (Isotope Inc.)	0.38 mm thick ⌀ 12.7 mm	0.008	8.086	75.096	16.81	0.474	8.03
SD-LiF-7-0.5 in teflon (Isotope Inc.)	0.5 mm thick ⌀ 8 mm	0.001	1.348	75.831	22.81	0.479	8.21
MR-LiF-7 in teflon (Isotope Inc.)	⌀ 1 mm 6 mm long	0.001	1.079	75.860	23.06	0.479	8.22
Rods (TLD-100) (Harshaw Co.)	⌀ 1 mm 6 mm long	1.980	24.77	73.25	—	0.463	7.50
Ribbons (TLD-100) (Harshaw Co.)	0.9 mm thick 3.2 mm × 3.2 mm	1.980	24.77	73.25	—	0.463	7.50

$\langle Z/A \rangle = \sum_j w_j \cdot \frac{Z_j}{A_j}$ (Bragg additivity rule)

$\bar{Z} = (\sum w_j \cdot Z_j^2/A_j)/(\sum w_j \cdot Z_j/A_j)$ BERGER 1971)

Density of LiF 2.64 g/cm^3, of LiF-teflon 2.2 g/cm^3.

Material and Methods

Dosemeter and read-out apparatus

Commercially available (Isotopes Inc. and Harshaw Co.) LiF dosemeters have been used. The different types of dosemeters and their isotopic abundances of ^{6}Li and ^{7}Li and atomic composition appear in Table 1. The thermoluminescence of the LiF dosemeters was measured in a Con-Rad reader (Model 5100A), which was modified to give higher gain and dynamic range, faster operation and lower drift and noise, and better reproducibility in the heating cycle. A Teledyne (Model TLD 7300) and a Harshaw (Model 2000 A and B) read-out apparatus were also used.

Method of irradiation

The irradiations were performed using a ^{60}Co therapy unit (Siemens Gammatron 3), a 6 MV linear accelerator (Varian Clinac 6), and a 42 MeV betatron (Siemens).

Table 2

Measured relative light signal per unit absorbed dose in polystyrene (density 1.045 g/cm³) for various radiations related to ^{60}Co gamma radiation for different LiF dosemeters. The conversion factors C_E or C_λ for polystyrene are given in the column marked C. With ^{60}Co gamma rays, $C_\lambda = 0.914$ (rad/'R')

				Relative light signal per dose in polystyrene					
Energy at surface E_0/MeV	Average energy at measuring depth $\bar{E}$/MeV	Measuring depth cm	C (rad/'R')	0.1 mm teflon discs	0.4 mm teflon discs	0.5 mm teflon discs	Harshaw 'High sensitivity' ribbons	Harshaw rods	Teflon rods
4.3	2.2	1.0	0.875	0.927	0.900	0.895	0.900	0.915	0.915
7.4	4.1	1.5	0.853	0.933	0.911	0.904	0.913	0.940	0.938
9.8	4.9	2.4	0.843	0.935	0.908	0.906	0.907	0.942	0.937
11.6	6.7	2.4	0.839	0.934	0.907	0.910	0.912	0.942	—
14.3	9.6	2.4	0.830	0.945	0.915	0.905	0.915	0.950	0.950
19.4	14.7	2.4	0.812	0.960	0.922	0.910	0.931	0.960	0.964
28.2	23.5	2.4	0.794	0.964	0.925	0.920	0.939	0.957	0.969
39.1	34.5	2.4	0.774	0.975	0.929	0.927	0.949	0.973	0.970
6 MV Rtg ray		1.5	0.894	0.971	0.958	0.951	0.981	0.972	—
42 MV Rtg ray		5.0	0.830	0.980	0.961	0.951	0.991	0.988	0.996

The energy of the electrons at the phantom surface was determined using the extrapolated range from depth ionization curves in water, and the energy at the depth employed was calculated using the approximation of a linear energy loss to the end of the extrapolated range (Nordic Association for Clinical Physics 1972). A polystyrene phantom was used, and the energies at the surface, the measuring depth and the average energies at measuring depth are given in Table 2.

Four or 6 dosemeters, the number depending on the kind of dosemeters that were used, were placed in a polystyrene plate at a depth depending on the energy used. The dosemeters were placed in such a way that non-uniformities in the radiation beam would influence the results negligibly and that the dosemeters would not disturb each other.

A beam monitor was used at the accelerators. The calibration of this monitor was determined before and after each experiment using a thimble ionization chamber placed in the polystyrene phantom with its symmetry axis displaced from the measurement depth by three quarters of its radius along the beam axis and away from the source. The thimble chamber was used as an additional monitoring chamber and positioned 12 mm beneath the thermoluminescent dosemeters during their irradiation. Its constancy was regularly checked against a ^{60}Co beam.

Measurement of thermoluminescent response

All results were referred to the thermoluminescent yield obtained at irradiation in a polystyrene phantom. It was possible to cancel the effects of fading in the LiF

dosemeters, since the time interval between the irradiation and the read-out of a dosemeter was kept the same in both calibration and experiment. The heating during the read-out procedure was used as the only method for preannealing (CARLSSON et coll. 1968). In order to allow identical cooling-cycles for all the dosemeters they were retained in the read-out apparatus one minute after the integration was completed. The dosemeters were calibrated in a ^{60}Co radiation therapy beam, the calibration constants being $C_i = \bar{X}/X_i$ where X_i is the thermoluminescent signal from dosemeter number i and $\bar{X}$ is the mean of all values of X_i. The calibration constants thus express the variation of the individual dosemeters around the mean (CARLSSON et coll.). Even though this mean varies from irradiation to irradiation, C_i remains constant for each dosemeter provided all of the dosemeters are subjected to exactly the same heating and cooling procedure (MÅRTENSSON 1969). Four or 6 dosemeters were calibrated each time a measurement series was performed. The observed range of the calibration constants of one individual dosemeter was about one per cent.

Determination of absorbed dose in polystyrene

All absorbed dose determinations are based on the exposure calibration with ^{60}Co gamma rays of the thimble chamber. The inaccuracy of this calibration cancels in the calculations of the relative energy dependence and the main remaining uncertainty in the absorbed dose determination should be that of the conversion factors used with the thimble chamber.

The absorbed dose in polystyrene was determined from the ionization chamber readings using the conversion factors C_λ given for photons by SCRAD (1971). For electrons the conversion factors (C_E) were calculated using the relationship taken from the recommendations of the Nordic Association for Clinical Physics (1972), with water replaced by polystyrene. The mass collision stopping power values for polystyrene and air were taken from BERGER & SELTZER (1964).

The absorbed dose determined in this way was checked at an average electron energy of 9.6 MeV, employing the absorbed dose calibration service with chemical dosimetry from the National Physical Laboratory in England. The resulting difference of less than 1.5 per cent was within the limits of error.

Results

Non-uniformity of dose within the dosemeters

The measurement of dosemeter response is subject to several uncertainties which have been thoroughly analysed by many authors: fading, supralinearity, sensitivity variations due to radiation and thermal history and the like. Repeated calibration of the dosemeters in a ^{60}Co gamma ray beam during similar conditions as those employed with other radiation qualities eliminates all of these systematic uncertainties except one. It is known that the heating of the dosemeter may be non-uniform and that significant attenuation in the dosemeter of the light emitted may occur. With the

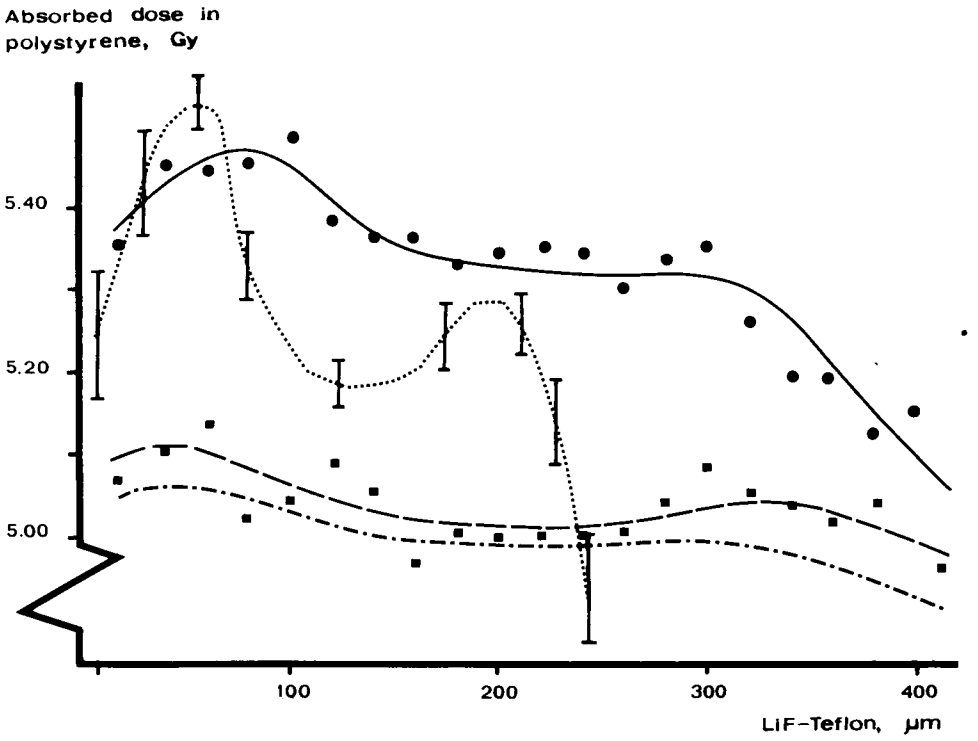

Fig. 1. The distribution of absorbed dose within 0.25 mm (diameter 12 mm, dotted curve) and 0.40 mm (diameter 6 mm) thick LiF-teflon discs, tightly packed and surrounded by polystyrene. Irradiation was with ^{60}Co gamma radiation, 42 MV roentgen radiation, and electrons of average energy at the measuring depth 34.5 MeV. The points in the figure show the spread of the results from the individual dosemeters (circles ^{60}Co, squares 34.5 MeV). The maximum deviations from repeated irradiations are also indicated by bars for some of the experimental points forming the dotted curve. —— ^{60}Co, ···· ^{60}Co, –– 34.5 MeV electrons, –·–·– 42 MV roentgen rays.

same distribution of dose within the dosemeter at the calibration and at a measurement with a different radiation quality, the same efficiency of light production and collection will result, provided that the dosemeters are all read out in the same geometry, i.e., if the dosemeters are not turned in any way with respect to one another. With different distributions of absorbed dose in the dosemeters, the production and collection efficiencies may differ resulting in a systematic error. A similar error will be caused by dosemeters exhibiting asymmetry about the main dosemeter plane, due for instance to bending of an elastic dosemeter material.

The dose within a dosemeter irradiated in a medium of different atomic composition may be significantly non-uniform (EHRLICH 1971, ALM-CARLSSON 1973, BERTILSSON 1975). Even with the high energy of ^{60}Co gamma rays, with a 0.2 mm thin disc-shaped dosemeter and with the small atomic number difference between polystyrene and lithium fluoride in teflon, the dose in the dosemeter may have a range of about

10 per cent (Fig. 1). The result was obtained by stacking several microtomed dosemeters during irradiation at 5 cm depth in a polystyrene phantom and then reading out the dosemeters individually. The beam size was 10 cm × 10 cm. The experiment was repeated at 0.5 cm depth, with no significant difference in the result. The figure also shows the corresponding curve for electrons of incident energy 39 MeV and irradiation depth 2.4 cm and 42 MV roentgen rays and irradiation depth 5 cm. Here, the dose difference within the dosemeter is about 3 per cent. Different radiation qualities thus give different distributions of absorbed dose within the dosemeter. The non-uniformity should be due to atomic number differences between the dosemeters and the phantom material. It might thus be more marked with other types of dosemeters.

The error from this non-uniformity due to the read-out procedure will depend on several factors influencing the light production and collection efficiency, such as the temperature gradient in the dosemeters and the reflecting properties of the read-out tray and the light attenuation in the dosemeter, which in turn might depend on its cleanness, temperature and thermal history. Correction factors calculated for one situation are thus not generally applicable, but should only be taken as indicators of the order of magnitude of possible effects.

BERTILSSON has discussed the magnitude of such an error, and suggested a model which should represent a typical case. When applied to the dashed curve of Fig. 1 it gives a correction for either read-out direction of somewhat less than 1 per cent as compared to a homogeneously irradiated dosemeter. The difference between the two possible read-out orientations would be about 1 per cent. A similar difference was obtained following irradiation of dosemeters at 0.5 cm depth in a polystyrene phantom using ^{60}Co gamma rays and 10 cm × 10 cm beam size. With the entrance side of 0.1 mm LiF teflon dosemeters turned towards the light detector during read out, about 1 per cent higher reading was found than when it was turned towards the heating planchet. This occurred with a routinely used nichrome planchet with a metal screen keeping the dosemeters in place, and using a Conrad reader. The corresponding figure with a 0.4 mm LiF-teflon disc was 8 per cent. With a new, silvered planchet and a Harshaw reader with no top grid, a difference less than 2 per cent was observed with a 0.9 mm LiF chip, but 6 per cent appeared when an old, poorly reflecting planchet was used. In some extreme cases more than 15 per cent difference with 0.4 mm LiF-teflon discs was observed.

With rods, the non-uniformity of the dose distribution should be less marked and there would be no preferred reading direction, so the error should be considerably smaller.

The conclusion is that a systematic error due to non-uniform dose distribution may amount to several per cent. With clean dosemeters, shining planchets and thorough heating of the dosemeter, it should be possible to keep the error below one per cent except in the case of 0.4 mm and 0.5 mm lithium fluoride teflon discs. With these, large differences between the two orientations were frequently obtained, which must

partly be due to other causes than the dose distribution, and eventually it was decided to discard the results as not meeting the accuracy demands. An error in the dose assessment of about 5 per cent was suggested. For routine clinical checks of, for instance, entrance and exit dose, these dosemeters should still be useful. In principle, a correction for the effect is possible. This would, however, presuppose many measurements made with high precision, and be subject to specification of a large number of experimental conditions, thus being quite impractical.

The non-uniformity effect would be almost completely eliminated if the dosemeter were surrounded by a wall of the dosemeter material having proper thickness. In the case of 0.13 mm thick LiF dosemeters, for instance, a wall of one dosemeter on either side will serve to give a quite uniform dose to the measuring dosemeter in between. The latter will cover the depth from 130 to 260 μm of the three curves in Fig. 1 obtained with 400 μm LiF-teflon. This was confirmed in an independent check with 13 0.01 mm thick dosemeters placed between two 0.13 mm dosemeters.

Relation between dosemeter response and phantom dose, and assigned error limits

The primary calibration of the dosemeters was performed in a ^{60}Co gamma ray beam. The ratio $A_{Co} = S_{Co}/D_{p,Co}$ of the thermoluminescent signal S_{Co} and the absorbed dose in polystyrene $D_{p,Co}$ was also used as the primary sensitivity factor at the other radiations, in the following denoted by subscript E. Since this common practice easily leads to confusion, the quantities used will be described in detail.

The relative yield of light detected per unit mean absorbed dose in the dosemeter will be denoted Y ($=S/D_L$). Then

$$S_E = A_{Co} \cdot D_{p,Co} \cdot D_{L,E} \cdot Y_E/(Y_{Co} \cdot D_{L,Co}) \quad (1)$$

Subscript L stands for the dosemeter material. The relative response k of the dosemeter is defined as the correction factor by which the ratio A_{Co} should be multiplied to give the ratio A_E applicable for the actual radiation quality, or $A_E = k\, A_{Co}$. Thus

$$k = D_{L,E} \cdot D_{p,Co} \cdot Y_E/(D_{p,E} \cdot D_{L,Co} \cdot Y_{Co}) \quad (2)$$

The results are expressed in Table 2 with the aid of the relative response, k. Some results relating to the isotopic composition of the lithium are discussed on page 165.

The resultant uncertainty in the relative response values is estimated to be mainly due to the ratio $D_{p,Co}/D_{p,E}$. The principal contributor here is the ratio of conversion factors C_λ or C_E. Two correction factors at high electron energies applicable to thermoluminescent dosemeters are discussed in equation 14. Similar correction factors should apply to the ionization chamber used, being each less than 2 per cent above 5 MeV electron energy. Below 5 MeV, they increase rapidly with decreasing energy, and the error in the conversion factor ratio may be as high as ± 5 % at about 2 MeV electron energy. At energies above 4 MeV, the consistency of several literature

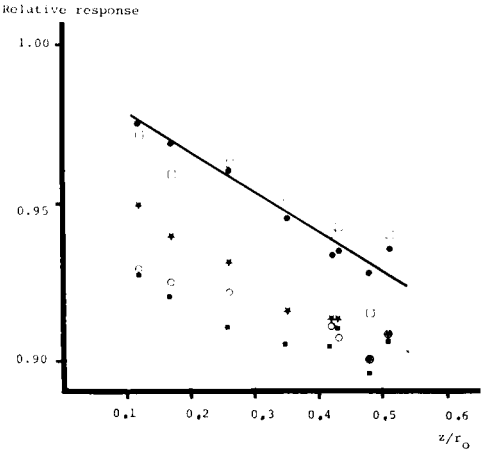

Fig. 2. The relative response for different kinds of LiF dosemeters to high energy electrons plotted as a function of irradiation depth (z) in units of the csda range (r_0). The ordinate is the relative response taken from Table 2. In order of increasing z/r_0, the points represent the following electron energies at the measuring depth: 34.5, 23.5, 14.7, 9.6, 4.1, 6.7, 2.2 and 4.9 MeV. The linear relationship is purely empirical, and as yet unexplained. ● 0.1 mm ⌀ 12.7 mm discs, □ 6 mm long ⌀ 1 mm rods, ★ 0.9 mm 3.2 mm × 3.2 mm ribbons, ○ 0.4 mm ⌀ 12.7 mm discs, ■ 0.5 mm ⌀ 8 mm discs.

comparisons of ionization and other types of dosimetry indicates a corresponding error of ±3% at electrons with energy below 5 MeV, ±2% at 42 MV photons and 5–10 MeV electrons, and ±1% at the other radiations.

A separate discussion was given in the previous paragraph concerning errors from non-uniform distributions of dose in the dosemeter. The precision in independent determinations of the response factors over a period of several years has been good with the results falling within ± 1 per cent apart from errors associated with the non-uniform dose distribution. The overall error in the relative response is thus in most cases about ±2%, the confidence of this interval being about 95%, but for electrons with energy 4–5 MeV it is estimated as ±3%, and at 2 MeV ±5%. Attention should be paid to the close correlation of the results for electrons with irradiation depth in units of the csda range (Fig. 2). A straight line fit is especially good for flat dosemeters with thickness 0.1 mm and 0.9 mm, the deviation typically being less than 0.5 per cent. The reason for this correlation is not clear.

Discussion

Influence of the dosemeter composition

The atomic composition of the dosemeters used is given in Table 1, along with the isotopic composition of the lithium. Some aspects on the isotopic composition have been discussed by ATTIX (1969).

A change in isotopic composition in pure LiF only influences the mass involved but not the interaction of electrons and photons with the atomic electrons and nuclei. Such a change with the atomic composition retained leads to a certain fractional change of the dosemeter density, and the inverse of this change will appear in the mass stopping power and mass energy absorption coefficient. In the case of LiF-teflon, however, the relative number of the various atoms is changed. The mass

stopping power and mass energy absorption coefficient should be approximately proportional to $\langle Z/A \rangle$ which is given in Table 1. About 1 per cent higher response would be expected from LiF-6-0.13 as compared with LiF-7-0.13 and LiF-N-0.13. In the experiments, the differences due to isotopic composition will cancel almost completely for the interactions mentioned.

In high-energy electron and photon beams other particles, particularly neutrons, may result from interactions with irradiated material such as collimators and the patient. The isotopic composition has been found significant in interactions with such particles in one case only, that of high energy photons which are associated with significant neutron contamination. With 42 MV photons, the LiF-6 dosemeters gave a 9 per cent higher response than LiF-7 and LiF-N dosemeters. With all other radiations used, no significant (< 1 %) difference in response existed between dosemeters of different isotopic composition.

Attention should also be paid to the previously mentioned apparent differences in transparency which may make the LiF-teflon dosemeters somewhat more amenable to systematic read-out error than the pure LiF dosemeters.

Calculation of dosemeter response using conventional cavity theory

A theoretical understanding of the relative response as defined in equation 2 is of considerable practical interest, since it might permit generalizations to conditions different from those actually investigated for instance concerning phantom material and irradiation depth. Such an understanding requires the elucidation of the three ratios $D_{L,E}/D_{p,E}$, $D_{p,Co}/D_{L,Co}$ and Y_E/Y_{Co}.

The latter may be influenced by the non-uniformity of dose in the dosemeter, as discussed on page 162 but with care the influence can be made negligible (< 1 %). Another potential influence is connected with the light production in the lithium fluoride crystals. The LET dependence here should also have a negligible effect of less than 1 per cent for the high energy radiations used (JÄHNERT 1972).

The main explanation for the deviations from unity of the relative response must be sought in the ratios of mean absorbed dose in the dosemeter and absorbed dose in the surrounding material. A first approximation is obtained from the use of the generalized mass stopping power ratio as defined for photons by BURLIN (1968) and from the mass stopping power ratio for electrons. The mass energy absorption coefficients of HUBBELL (1969) as tabulated by SINCLAIR (1969) was used. The complete photon spectrum from the ^{60}Co teletherapy machine was included, yielding a mass energy absorption coefficient ratio of LiF to polystyrene which is about 1 per cent higher than that at 1.25 MeV. The accuracy of the calculated coefficients and their ratios is believed to be better than 1 per cent. In the case of photons, the mass stopping-power ratios were determined at the mean secondary electron energy, which was obtained from GREENE & MASSEY (1966) and ICRU (1964) and for the electrons the mass stopping-power ratios were determined at the mean energy of the primary electrons at the actual depth. The accuracy of the stopping power values

Table 3

Calculated and measured responses relative to that at ^{60}Co. The theoretical values designated BURLIN *are determined using* BURLIN'S *theory for photons and the stopping power ratio for electrons*

	0.1 mm LiF-teflon discs			0.9 mm LiF ribbons			Uncertainty of experiments
	Calculated		Measured	Calculated		Measured	
	BURLIN	This work		BURLIN	This work		
Electrons							
2.2 MeV	0.98		0.93	0.97		0.90	±0.05
4.1 MeV	0.98		0.93	0.97		0.91	±0.03
4.9 MeV	0.98	0.99	0.94	0.98	0.98	0.91	±0.03
6.7 MeV	0.98		0.93	0.98		0.91	±0.02
9.6 MeV	0.99		0.95	0.98		0.92	±0.02
14.7 MeV	1.00		0.96	0.98		0.93	±0.02
23.5 MeV	1.00		0.97	0.98		0.94	±0.02
34.5 MeV	1.00	0.99	0.98	0.98	0.97	0.95	±0.02
Rtg radiation							
6 MV	0.98	0.99	0.97	0.98	0.99	0.98	±0.02
42 MV	0.99	0.99	0.98	0.98	0.97	0.99	±0.02

(BERGER & SELTZER 1964, 1966, BERGER 1973 a) is quoted to be about 2 per cent, and their ratios for compounds with small atomic number differences are probably more accurate.

The data derived in this way appear in Table 3. They approximate the experimental results for electrons to about 5 per cent. The variation of the dosemeter response with electron energy is partly but not fully accounted for. For photons the agreement is better.

Alternatives to conventional cavity theory

The cavity theory by BURLIN does not account for the phenomena caused by differences in electron scattering properties of the dosemeter and the phantom material. Further discussion has been given by, for instance, ALMOND & MCCRAY, BURLIN (1970), JANSSENS et coll. (1974), HOLT et coll. and BERTILSSON. Some suggestions for a different cavity theory for flat dosemeters are now presented, describing the results to about the same degree of approximation as the BURLIN theory. The approach or a similar one should be necessary to describe the results obtained with higher atomic number dosemeters in tissue-like media. It is to be hoped that further elaboration might lead to better approximations also in the case of lithium fluoride dosemeters.

The present theory rests upon separate treatment of three parts of the electron spectrum. The low-energy spectrum contains electrons with ranges small compared with the dosemeter dimensions. In the high-energy spectrum the ranges are com-

paratively large, and at intermediate energies they are comparable with the dosemeter dimensions.

Low energy electrons. With the energies limited by $r_0/T < 2$, incident low energy electrons (csda range r_0) are almost completely absorbed in the dosemeter (thickness T), the absorbed dose at the exit surface of the dosemeter being less than 15 per cent of that at the entrance (as calculated using data by BERGER 1973).

Interface effects from low energy electrons can be accounted for as follows. The following symbols are used:

b absorbed dose backscatter factor of low energy electrons isotropically incident on a medium
D_I absorbed dose at the interface, J/kg
D equilibrium absorbed dose, J/kg
s collision mass stopping power, J m^2/kg
ϕ_F spherical fluence of low energy electrons in the forward direction generated before the considered plane, m^{-2}
ϕ_B ditto in the backward direction, generated after the plane
C constant of proportionality
Z atomic number

A dosemeter with a certain atomic composition is placed in a medium of a different atomic composition. Quantities pertaining to the dosemeter and the medium are primed and un-primed, respectively.

The low energy electrons in either half-space are assumed to have isotropic angular distribution, which is not changed by the reflections. Their absorbed dose contribution is proportional to the spherical particle fluence and the collision mass stopping power. Assuming approximately the same change in stopping power following each reflexion, the absorbed dose backscatter factor will not change, since the number albedo is approximately energy independent above a certain minimum energy. The absorbed dose from successive reflections will be

$$D_I = Cs(\phi_F(1 + b^1 + bb^1 + bb^{1^2} + b^2b^{1^2} + - - -) + \phi_B^1(1 + b + bb^1 + b^2b^1 + b^2b^{1^2} + - - -)$$

$$\text{or } D_I = Cs(\phi_F(1 + b^1) + \phi_B^1(1 + b))/(1 - bb^1)) \quad (3)$$

obtained through geometric series summation. A similar detailed derivation is given by ALM-CARLSSON.

Take first a point in a homogeneous medium, where $b = b^1$ and $\phi = \phi^1$. Then

$$D = C\ s(\phi_F + \phi_B)/(1 - b) \quad (4)$$

$$D^1 = C\ s^1(\phi_F^1 + \phi_B^1)/(1 - b^1) \quad (5)$$

Equations 4 and 5 say that with a given particle fluence the absorbed dose would be expected to be proportional to $s/(1 - b)$, where b is the absorbed dose albedo for

isotropic incidence. This value at low atomic numbers may be estimated from the data for mylar and aluminium by ALM-CARLSSON to be

$$b = 0.40 + 0.010\ Z \tag{6}$$

It is immediately interesting to analyse the ratio of absorbed doses expected in two media subjected to the same electron fluence; thus

$$D/D^1 = s(1 - b^1)/(s^1(1 - b)) \tag{7}$$

Taking water as the reference medium with $Z^1 = 6.6$ in the range $Z = 5$ to $Z = 20$

$$D/D^1 \simeq s(1 + 0.023(Z - 6.6))/s^1 \tag{8}$$

is found. This happens to be very closely the same formula as that of the relative attenuation factor given by BERGER (1971), but considering the uncertainties involved and the different approaches, the numerical agreement is fortuituous. Nevertheless, the similarity of the expressions indicates that the approximate considerations based on backscattering properties might be justified for the present purposes.

From equations 3 and 4 the absorbed dose in the medium at the interface is found to be

$$D_I = D\ (1 - b)\ [\phi_F(1 + b^1) + \phi_B{}^1(1 + b)]\ (1 - bb^1)^{-1}(\phi_F + \phi_B)^{-1} \tag{9}$$

By assuming $\phi_B^1 \simeq \phi_B$ then $D_I = D(1 + b^1 - b + c)$, where c is a small correction term. Changing to the absorbed dose in the dosemeter and using equation 6

$$D_I^1 = D(1 + 0.010(Z^1 - Z) + c)s^1/s \tag{10}$$

The correction term c is less than about $\pm 0.05\ \phi_B/\phi_F$. The atomic number dependence will thus be dominated by the simple term $0.01\ (Z^1 - Z)$ when the low energy electrons are generated primarily in the forward direction.

The absorbed dose disturbance at the interface is attenuated to 1/e ('relaxation length' equivalent) at a depth of 0.1 T, according to the results for ^{60}Co. This is not surprising since it is known from beta spectra that a corresponding attenuation is obtained at about 0.05 of the csda range of the maximum energy electrons (in the range 0.2–1 MeV, derived from data by BERGER 1971 and 1973). Assuming exponential attenuation, the relative change of average dose in the dosemeter due to the interface disturbance is by integration over the dosemeter mass using equations 8 and 10 ($c = 0$)

$$a_L \simeq -0.1\ RT \cdot 0.013\ (Z^1 - Z) \tag{11}$$

where R is the ratio of the surface area and the mass of the dosemeter. When the dosemeter diameter is much greater than the thickness, $RT = 2$ and

$$a_L \simeq -0.003\ (Z^1 - Z) \tag{12}$$

The attenuation of the low energy spectrum further away from the interface is dependent on the attenuation of higher energy electrons from which the low energy spectrum is partly derived. These higher energy electrons should also have preference for the forward directions. Consequently the fluence of low energy electrons originating from electrons in the medium will change more slowly than the fluence of electrons which are directly involved in the interface phenomena. This change has been neglected, but this approximation is obviously poor in the case of ^{60}Co irradiation (Fig. 1).

The approximate energy independence of the number albedo holds well, down to about 10 keV (HARDER 1969). Below this energy, the albedo decreases, particularly at high atomic numbers. As a consequence, the electron path pattern becomes nearly independent of the atomic number, as demonstrated for instance by the detour factor (HARDER 1969), if it is assumed that differences in atomic number at an interface do not influence the energy deposition pattern of electrons below 10 keV. The energy of delta electrons below 10 keV is thus considered to be locally absorbed.

Intermediate energy electrons. With intermediate energy electrons, $2 \leq r_0/T \leq 5$, both backscattering and transmission must be accounted for. The backscattered electrons have lower energy and thus pass partly into the low energy domain. The dose albedo might also be lower than for low energy electrons, since electron energies of the order of 1 MeV are being approached. An error of much less than 1 per cent will result from neglecting the backscattering. However, with larger atomic number differences and these electrons contributing a large fraction of the absorbed dose, a separate backscattering correction should be made.

The energy absorption of intermediate energy electrons is difficult to evaluate. As a first approximation, the assumption of a linear depth dose curve reaching zero at a depth of twice the dosemeter thickness is suggested. This may be reasonable since the mean of the range interval is at 3.5 T, and only a few per cent of the absorbed dose should remain at $0.6\ r_0 = 2.1$ T (BERGER 1973). The remaining absorbed dose is made up for by electrons generated inside the dosemeter, their number being characterized by the collision mass stopping power s_H of the high energy electrons. The penetration is still assumed to be characterized by the relative attenuation factor (equation 8). With these assumptions

$$D^1 = D(1 + 0.023\ (Z^1 - Z))\ (s_I^1/s_I)\ (0.75 + 0.25\ s_H^1/s_H) \tag{13}$$

is found for the intermediate energy electrons.

Again, there may be some details of the attenuation which are not covered by the approximation (Fig. 1).

High energy electrons. About 80 per cent or more of the energy of high energy electrons ($r_0/T > 5$) perpendicularly incident on the dosemeter will be transmitted

through it (SELTZER & BERGER 1974). The fractional increase in absorbed dose due to the longer average path length caused by multiple scattering can be calculated using the mass scattering power ν (defined in ICRU 1972) of the incident electrons (BRAHME 1975). By definition, the rms angle of deflection at a depth x is $\sqrt{\nu x}$, and the relative absorbed dose will be the inverse cosine of this, which in a small angle approximation is $1+\nu x/2$. Integrated over the dosemeter thickness ϱT, a correction term $\nu T\varrho/4$ results. This approximation will be poor only at the highest atomic number ($Z=20$) and lowest energy (0.4 MeV) considered. The mass scattering power is as a first approximation evaluated at the geometrical mean of the upper and lower limit of the high energy electron interval. This approximation would hold exactly if the absorbed dose contribution were the same for electrons of different energies and the mass scattering power were inversely proportional to the square of the electron energy.

The scattering of electrons is strongly discontinuous. Even though the average path length in a slab can be well described, some paths are lost completely through scattering out through the sides of a finite size dosemeter. Whether or not these are compensated for by in-scattering depends on the density and atomic number of the surrounding medium. Analytic expressions for the correction, p, describing loss or surplus of tracks from scattered electrons can be derived (HARDER 1968) for a variety of dosemeter shapes. The energy at the middle of the high energy interval will be used for calculating the correction.

If either of the high energy corrections will influence the resultant generalized stopping power ratio by more than one per cent, it should be viewed with great distrust because of the approximations involved. A thinner dosemeter will give a smaller correction.

The backscattering difference between the dosemeter and the medium in connection with high energy electrons is neglected. Thus the absorbed dose in the dosemeter is assumed to be given by

$$D^1 = D((1+(\nu^1-\nu\varrho/\varrho^1)T/4)+p)(s^1_H/s_H) \tag{14}$$

Photon irradiation. In the case of photon irradiation, the transition to an electron spectrum characterized by the mass energy absorption coefficient of the dosemeter at larger dosemeter thicknesses should be accounted for. The attenuation of the electron spectrum can be approximately calculated using the data by BERGER (1973). The approximation was made, that the range of electrons with the mean energy of the initial electron spectrum is relevant to describe the attenuation. This is supported by the fact that with beta spectra, the attenuation to 1/e of the source energy is about the same as that of monoenergetic spectra with the mean beta energy, that is one third of the maximum beta energy, as obtained from the percentile distance data by BERGER (1971). An exponential decrease of the absorbed dose from the interface (BERGER 1973) is thus assumed, with attenuation to 1/e at a depth of 0.3 times the csda range $\bar{r}$ of electrons with the mean energy of the initial spectrum. The fraction

Table 4

Examples concerning the calculation of dosemeter response from equation 16

		0.13 mm LiF-teflon discs $Z^1 = 8.03$, $Z = 5.29$ $-p < 0.002$ (all electron energies) $\mu^1/\mu = 0.88$				0.9 mm LiF ribbons $Z^1 = 7.50$, $Z = 5.29$ $p = -0.012$ (4.9 MeV) $\mu^1/\mu = 0.86$			
		Energy interval MeV				Energy interval MeV			
		Low	Inter-mediate	High	Total	Low	Inter-mediate	High	Total
		<0.2	0.2–0.4	>0.4		<1.0	1.0–2.2	>2.2	
^{60}Co	s^1/s	0.825	0.833	0.837		0.820	—	—	
	h	0.4	0.3	0.3	1.000	1.0	0	—	1.000
	h^1/h	0.878	0.844	0.860		0.865	—	—	
	h^1	0.351	0.253	0.258	0.862	0.865	0	—	0.865
4.9 MeV e^-	s^1/s	0.825	0.833	0.836		0.822	0.826	0.828	
$Z/r_0 = 0.5$	h	0.2	0.1	0.7	1.000	0.4	0.3	0.3	1.000
	h^1/h	0.878	0.844	0.844		0.865	0.825	0.835	
	h^1	0.176	0.084	0.591	0.851	0.346	0.248	0.250	0.844

d of the total absorbed dose which is contributed by electrons generated by photon interactions outside the dosemeter is then given by

$$d = (\bar{r}/3T)(1 - \exp(3T/\bar{r})) \tag{15}$$

The approximation will be particularly poor at high photon energies where for instance the assumption about isotropy is not valid, but it may still be acceptable since d is approaching unity when $\bar{r} \gg T$. In the case of electron irradiation, $d = 1$.

The relation should in fact rather be characterizing the case when the dosemeter has the same composition as the surrounding medium. The actual dosemeter material is accounted for approximately in two ways. First, the dosemeter response to photons averaged over all electron energies is assumed to be proportional to the rate of generation of electrons within it, which is μ^1/μ times higher than in the medium. Secondly, for the interface effects of the low energy part of the electron spectrum, the difference in mass energy absorption coefficient is neglected, and a correction factor, independent of d, is applied.

Application. The resultant mean absorbed dose in the dosemeter will be approximately given by the following expression, where h denotes the fraction of absorbed dose contributed by electrons in the energy interval:

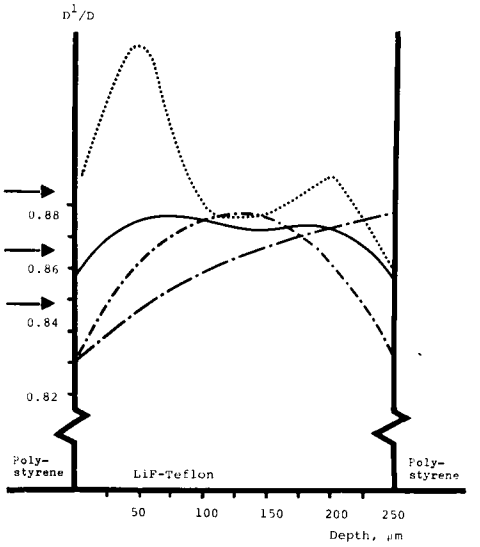

Fig. 3. Absorbed dose ratio D^1/D of the dose in LiF-teflon dosemeter and the dose in surrounding polystyrene. Irradiation with ^{60}Co. The curves marked Burlin give the mean absorbed dose of the BURLIN theory, and the shape is an exponential transition from the mass collision stopping power ratio to the mass energy absorption coefficient ratio. The arrows to the left mark the direction of irradiation. ···· experiment, —·— BURLIN, one-sided, —— present investigation, theory, –·– BURLIN, double-sided.

$$\begin{aligned} D^1/D = {} & d(h_L(1+0.023(Z^1-Z))(s_L^1/s_L) \\ & + h_I(0.75+0.25s_H^1/s_H)(1+0.023(Z^1-Z))(s_I^1/s_I) \\ & + h_H(1+(\nu^1-\nu\varrho/\varrho^1)T/4+p)(s_H^{11}/s_H)) \\ & + (1-d)\mu^1/\mu - 0.003h_L(Z^1-Z) \end{aligned} \tag{16}$$

The following notation will be used:

$$D^1/D = d(h_L^1+h_I^1+h_H^1)+(1-d)\mu^1/\mu - 0.003h_L(Z^1-Z) \tag{17}$$

An illustration to the type of calculation is given in Table 4, which gives an idea of the relative importance of the various correction factors. The assessment of absorbed dose fraction h in the three energy intervals was crudely made with the aid of spectra of fluence versus energy and cumulative absorbed dose versus energy given in several sources (ICRU 1964, 1970, 1972, KESSARIS 1970). The end results are given in Table 3. The mean absorbed dose in the dosemeter is probably described to the same degree of accuracy as in the BURLIN theory. However, the distribution of absorbed dose in the dosemeter should be more correctly described by the present model. This is illustrated in Fig. 3, which gives the dose distribution from Fig. 1 in the case of a 0.25 mm thick LiF-teflon dosemeter irradiated in polystyrene using ^{60}Co gamma rays. The mean absorbed dose in the dosemeter was 5 per cent higher than the mean dose in a 0.01 mm dosemeter irradiated under otherwise identical conditions. Both the BURLIN theory and the present model predict a 4 per cent higher response. The measured and some calculated dose distributions are given in the figure in units of the absorbed dose in polystyrene.

The relative polystyrene dose from the experiment was calculated using the model, applied to the 0.01 mm dosemeter. The distribution from the BURLIN theory is not easily obtained and only its main features are illustrated. The transition from the mass stopping power ratio to the mass energy absorption coefficient ratio is clearly insufficient as a description, whether this transition goes from the direction of incidence (more likely) or equally from the two sides. The present description is also insufficient but seems to be a better approximation to the experiment.

Conclusions

Thermoluminescent dosemeters based on lithium fluoride can be used with high precision in clinical dosimetry. The present work has confirmed the complexity of high energy radiation interactions with intermediate sized dosemeters in phantoms. Some problems have been shown to be connected with the particular dosemeters used. If for instance precision and accuracy on the per cent level are required, then 0.4 mm and 0.5 mm thick lithium fluoride teflon dosemeters should not be used because of problems connected with light production and collection during the read out procedure. In lithium fluoride dosemeters, further, the content of lithium 6 gives significant problems only in dosemeters enriched in lithium 6 used with high energy bremsstrahlung.

Other problems are associated with the differences in atomic number between the dosemeter and the medium, causing interface effects which may influence the mean absorbed dose in the dosemeter on the percentage level in commonly encountered situations. These interface effects could be significantly reduced if the dosemeter is surrounded by walls of identical composition.

With photon irradiation the difference between experimental dosemeter response and theory is within the experimental error of $\pm 2\%$. With electron beams similar consistency is obtained at high energies but at low energies the dosemeter response is unexpectedly up to 5 per cent lower than at the highest energies. This might partly be explained by errors in the ionization chamber measurements. In a further explanation one might possibly utilize the finding that the dosemeter response is linearly related to the ratio of irradiation depth and electron range.

SUMMARY

The relative light output per Gy in polystyrene for roentgen beams of 6 and 42 MV and electrons between 2.2 and 34.5 MeV relative to ^{60}Co gamma radiation is reported for different kinds of LiF dosemeters. The distribution of the absorbed dose inside a 0.25 and 0.4 mm thick LiF-teflon disc surrounded by polystyrene and irradiated with ^{60}Co, 42 MV roentgen radiation and 39 MeV electrons was measured using 0.01 and 0.02 mm thick Lif-teflon discs. The measurements show that the absorbed dose distribution in the dosemeter depends on the energy of the radiation. When flat dosemeters were used, differences between the

signals measured at the two orientations possible during read-out could easily amount to several per cent, and for this reason 0.4 mm and 0.5 mm LiF-Teflon discs were not trusted when the highest accuracy was required. The cavity theory by BURLIN does not account for the phenomena caused by differences in electron scattering properties of the dosemeter and the phantom material. Some suggestions are presented for a different cavity theory for flat dosemeters dealing also with these phenomena. It describes the results to about the same degree of approximation as the BURLIN theory, and fails to explain the observed energy dependence for electrons.

ZUSAMMENFASSUNG

Die relative Lichtausbeute per Gy in Polystyren für Röntgenstrahlen von 6 und 42 MV und Elektronen zwischen 2,2 und 34,5 MeV relativ zu ^{60}Co Gammastrahlung für unterschiedliche Arten von LiF Dosimetern wurde gemessen. Die Verteilung der absorbierten Dosis innerhalb einer 0,25 und 0,4 mm dicken LiF-teflon Scheibe umgeben von Polystyren und bestrahlt mit ^{60}Co, 42 MV Röntgenstrahlung und 39 MeV Elektronen wurde unter Verwendung von 0,01 und 0,02 mm dicken LiF-teflon Scheiben gemessen. Die Messungen zeigen, dass die Verteilung der absorbierten Dosis im Dosimeter von der Energie der Bestrahlung abhängt. Wenn flache Dosimeter verwendet wurden, konnten ohne Schwierigkeit Unterschiede zwischen den gemessenen Signalen bei zwei während der Auswertung möglichen Orientierungen von mehreren Prozent erreicht werden, deshalb sind 0,4 mm und 0,5 mm LiF-teflon Scheiben nicht zuverlässig, wenn die höchste Genauigkeit verlangt wird. Die Kavitätstheorie von BURLIN kann nicht für das Phänomen verantwortlich gemacht werden, das durch Unterschiede in den Elektronen-streuenden Eigenschaften des Dosimeters und des Phantommaterials hervorgerufen werden. Einige Vorschläge für eine neue Kavitätstheorie für flache Dosimeter, die auch dieses Phänomen haben, werden vorgelegt. Diese beschreibt die Ergebnisse bis zu etwa dem gleichen Grad einer Annäherung wie die BURLIN-Theorie, und versagt um die beobachtete Energieabhängigkeit für Elektronen zu erklären.

RÉSUMÉ

Les auteurs ont mesuré pour différents types de dosimètres au LiF l'émission relative de lumière par Gy dans le polystyrène pour des faisceaux de rayons de Roentgen de 6 et de 42 MV et pour des électrons entre 2,2 et 34,5 MeV par rapport à la radiation gamma du ^{60}Co. La distribution de la dose absorbée dans un disque de téflon au LiF épais de 0,25 et de 0,4 mm, entouré de polystyrène et irradié par le ^{60}Co, la radiation Roentgen de 42 MV et les électrons de 39 MeV a été mesurée en utilisant des disques de téflon au LiF épais de 0,01 et 0,02 mm. Ces mesures montrent que la distribution de dose absorbée dans le dosimètre dépend de l'énergie de la radiation. Quand on utilise des dosimètres plats, les différences entre les signaux mesurés dans les deux orientations possibles au cours de la lecture peuvent aisément s'élever à plusieurs unités pour cent, c'est pourquoi les auteurs ne se sont pas fiés aux disques de téflon au LiF de 0,4 mm et de 0,5 mm, quand une très grande précision est nécessaire. La théorie de la cavité de BURLIN ne rend pas compte des phénomènes causés par les différences dans les propriétés de diffusion des électrons du dosimètre et du matériau du fantôme. Les auteurs font certaines suggestions concernant une théorie de la cavité différente pour les dosimètres plats et prenant en compte ces phénomènes. Cette théorie décrit les résultats avec à peu près le même degré d'approximation que la théorie de BURLIN mais n'explique pas la dépendance par rapport à l'énergie observée pour les électrons.

REFERENCES

ALM-CARLSSON G.: Dosimetry at interfaces. Theoretical analysis and measurements by means of thermoluminescent LiF. Acta radiol. (1973) Suppl. No. 332.

ALMOND P. R. and MCCRAY K.: The energy response of LiF, CaF_2 and $Li_2B_4O_7$: Mn to high energy radiations. Phys. in Med. Biol. 15 (1970), 335.

ATTIX F. H.: Isotopic effect in lithium fluoride thermoluminescent dosemeters. Phys. in Med. Biol. 14 (1969), 147.

BERGER M. J.: Distribution of absorbed dose around point sources of electrons and beta particles in water and other media. J. nucl. Med. (1971) Suppl. No. 5, p. 7.

— (a): Personal communication (1973).

— (b): Improved point kernels for electron and beta ray dosimetry. NBS Interagency report 73–107. Washington D.C. 1973.

— and SELTZER S. M.: Tables of energy losses and ranges of electrons and positrons. SP-3012, National Aeronautics and Space Administration, Washington, D.C. 1964.

—— Additional stopping power and range tables for protons mesons and electrons. SP-3036, National Aeronautics and Space Administration, Washington, D.C. 1966.

BERTILSSON G.: Electron scattering effects on absorbed dose measurements with LiF-dosemeters. Thesis. Report LURI 1973-13 University of Lund, Lund, Sweden (1975).

BRAHME A.: Simple relations for the penetration of high energy electron beams in matter. SSI: 1975-011, National Institute of Radiation Protection, Stockholm, Sweden (1975).

BURLIN T. E.: Cavity-chamber theory. *In:* Radiation Dosimetry. Vol. 1. Ed. by F. H. Attix and W. C. Roesch. Academic Press, New York and London 1968.

— The energy response of LiF, CaF_2 and $Li_2B_4O_7$ to high energy radiations. Phys. in Med. Biol. 15 (1970), 558.

— SNELLING R. J. and OWEN B.: The application of general cavity ionization theory to the dosimetry of electron fields. *In:* Proc. 2nd Symp. on Microdosimetry, Stresa, Italy, Oct. 1969 (Brussels: Commission of European Communities) p. 455.

CARLSSON C. A., MÅRTENSSON B. K. A. and ALM-CARLSSON G.: High precision dosimetry using thermoluminescent LiF. *In:* Proc. 2nd Int. Conf. on Luminescence Dosimetry. Conf-680920 (US AEC: Washington, D.C.), (1968), 936.

EHRLICH M.: Influence of size of CaF_2: Mn thermoluminescence dosimeters on ^{60}Co gamma-ray dosimetry in extended media. *In:* Proc. 3rd Int. Conf. on Luminescence Dosimetry. Risø Report No. 249 (1971), 550.

GREENE D. and MASSEY J. B.: The use of Farmer-Baldwin and Victoreen ionization chambers for dosimetry of high energy X-radiation. Phys. in Med. Biol. 11 (1966), 569.

HARDER D.: Einfluss der Vielfachstreuung von Elektronen auf die Ionisation in gasgefüllten Hohlräumen. Biophysik 5 (1968), 157.

— Some general results from the transport theory of electron absorption. *In:* Proc. 2nd Symp. on Microdosimetry, Stresa, Italy, Oct. 1969 (Brussels: Commission of European Communities) p. 567.

HOLT J. G., EDELSTEIN G. R. and CLARK T. E.: Energy dependence of the response of lithium fluoride TLD rods in high energy electron fields. Phys. in Med. Biol. 20 (1975), 559.

HUBBELL J. H.: Photon cross sections, attenuation coefficients and energy absorption coefficients from 10 keV to 100 GeV. Report NSRDS-NBS 29, National Bureau of Standards, Washington, D.C. 1969.

International Commission on Radiation Units Measurements (ICRU): Report No. 10 b: Physical aspects of irradiation. NBS Handbook 85, Washington, D.C. 1964.

— Report No. 16: Linear Energy Transfer. Washington, D.C. 1970.

— Report No. 21: Radiation Dosimetry: Electrons with Initial Energies between 1 and 50 MeV. Washington D.C. 1972.

JÄHNERT B.: The response of TLD-700 thermoluminescent dosimeters to protons and alpha particles. Hlth Phys. 23 (1972), 112.

JANSSENS A., EGGERMONT G., JACOBS R. and THIELENS G.: Spectrum perturbation and energy deposition models for stopping power ratio calculations in general cavity theory. Phys. in Med. Biol. 19 (1974), 619.

KESSARIS N. D.: Spectra of high-energy electron beams in water. Radiat. Res. 43 (1970), 281.

MÅRTENSSON B. K. A.: Thermoluminescence of LiF: A statistical analysis of the influence of preannealing on the precision of measurement. Phys. in Med. Biol. 14 (1969), 119.

Nordic Association for Clinical Physics: Procedures in radiation therapy dosimetry with 5 to 50 MeV electrons and roentgen and gamma rays with maximum photon energies between 1 MeV and 50 MeV. Acta radiol. Ther. Phys. Biol. 11 (1972), 603.

PALIWAL B. R. and ALMOND P. R.: Applications of cavity theories for electrons to LiF dosemeters. Phys. in Med. Biol. 20 (1975), 547.

RUDÉN B.-I.: Two years experience of clinical thermoluminescence dosimetry at the Radiumhemmet. *In:* Proc. 3rd. Int. Conf. on Luminescence Dosimetry. Risø Report No. 249 (1971), 781.

— and NILSSON B.: Clinical dosimetry by means of thermoluminescent dosemeters. *In:* Proceedings of XIII International Congress of Radiology, Madrid 1973. Part II, p. 495. Excerpta Medica, Amsterdam 1975.

SELTZER S. M. and BERGER M. J.: Transmission and reflection of electrons by foils. Nucl. Instr. and Meth. 119 (1974), 157.

SINCLAIR W. K.: Radiobiological dosimetry. *In:* Radiation Dosimetry. Vol. 3. Ed. by F. H. Attix and E. Tochilin. Academic Press, New York and London 1969.

SPENCER L. V.: Energy dissipation by fast electrons. National Bureau of Standards Monograph No. 1, (1959).

Sub-Committee on Radiation Dosimetry of the American Association of Physicists in Medicine (SCRAD): Protocol for the dosimetry of X- and gamma-ray beams with maximum energies between 0.6 and 50 MeV. Phys. in Med. Biol. 16 (1971), 379.

TURNER A. P. and ANDERSON D. W.: Thermoluminescent response of lithium fluoride to high energy photons. Phys. in Med. Biol. 18 (1973), 46.