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AUTOMATED THERMOLUMINESCENCE READER

II. Experiments and theory

B. LINDSKOUG

Solid state dosimeters have rapidly achieved acceptance in the medical and biologic fields (IAEA 1967). In clinical dosimetry, thermoluminescence dosimeters have proved to be particularly valuable (D.A.E.C. 1971), partly for practical reasons. The clinical environment necessitates easily handled and chemically and mechanically robust dosimeters. Thermoluminescence dosimeters of LiF-teflon (BJÄRNGARD et coll. 1967) have particularly good properties in these respects. They are mechanically flexible but nevertheless strong and they can be cleaned with various solvents and sterilized without being damaged.

Inconveniences in connection with the clinical use of TLD are the annealing procedures required to return the dosimeter material to its original sensitivity (CAMERON et coll. 1964, ZIMMERMAN et coll. 1966) and the manual work with forceps or a dispenser. Simplification of the annealing procedure and automation of the method of reading is highly desirable in connection with the clinical application of TLD particularly in laboratories with a high patient load.

In the first part of this work (LINDSKOUG & BENGTSSON 1975) a technical description of an automated TLD reader intended for radiation therapy dosimetry was given. The present second part presents an experimental investigation performed with the TLD reader and discussion of the results.

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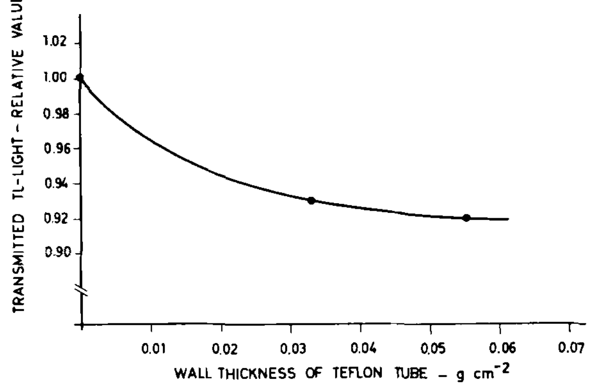

Fig. 1

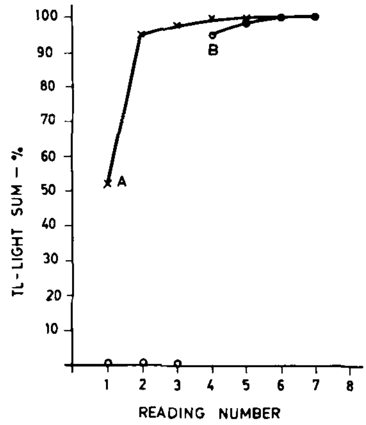

Fig. 2

Fig. 1. Fraction of thermoluminescent light transmitted through tubes of teflon with varying wall thicknesses.

Fig. 2. Initial response of TL-light sum normalized to last reading. A. Irradiation and reading. B. Reading three times before irradiation.

Experimental investigation

The special design and use of the measuring probes in this dosimetry system necessitates extensive experiments under varying conditions. A detailed description of the instrument and dosimeters is given in part I, which also includes a brief description of the technical function and use of the instrument. It should be mentioned that a reading means that the dosimeter material passes through first a pre-heater oven and then a read-out oven with a constant rate. Peaks in the glow curve cannot be resolved in this system and therefore the TL-light sum emitted in the read-out oven was always recorded.

The dosimeters used consist of cylindrical rods of LiF-teflon (MR-LiF-7, Teledyne, 1 mm $\times$ 6 mm) in teflon tubes of wall thickness 0.25 mm. Unless otherwise stated the following experiments were performed with 18 mm long dosimeters (three dosimeters of the length 6 mm close together) and the integrated signal was recorded. Integrating the signals from three dosimeters ensures good precision. The short measuring probes are more easy to keep clean than long chains of probes.

The temperatures were determined with a thermocouple of alumel-chromel enclosed in a teflon tube; external diameter 1.5 mm, internal diameter 0.5 mm. This thermocouple was transported through the pre-heater and read-out ovens in the same way as the dosimeter material. The peak temperature was recorded. The dosimeters were usually irradiated with a cylindrical ^{90}Sr-^{90}Y β-source (see part I). In this case absorbed dose stated refer to absorbed dose of ^{60}Co γ-ray in polystyrene, calculated as described in the section 'Calculation of absorbed dose' below. Where other radiation sources were used, this is stated specifically.

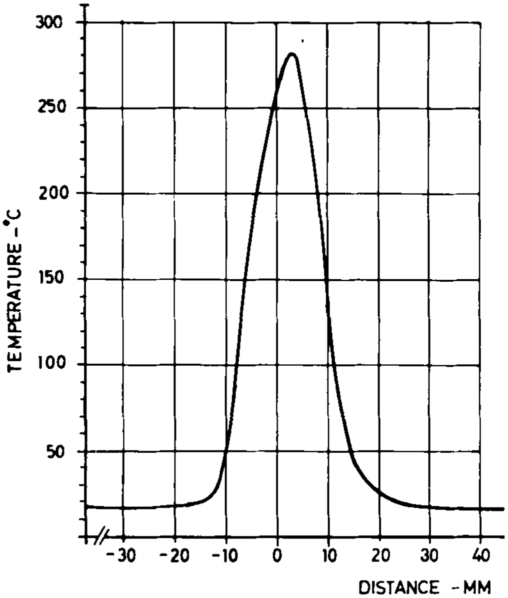

Fig. 3. Thermal course in the read-out oven.

Light absorption in teflon tubes. A 150 mm long rod of LiF-teflon was used to determine the absorption and reflection of light in the teflon tube surrounding the dosimeters. The long dosimeter could be read without the tube by inserting 4 mm of its end into a leader-probe. The irradiated dosimeter was read with and without the teflon tube. The result for two different wall thicknesses relative to the uncovered dosimeter is illustrated in Fig. 1. The emitted light is reduced by approximately 8 per cent with the wall thickness 0.055 g cm^{-2}, which is the dimension normally used in a measuring probe.

Initial response. The heating of the dosimeter material during reading causes an increase in sensitivity of the dosimeter material. The initial responses of two previously untreated dosimeters are plotted in Fig. 2. Curve A represents an increase in sensitivity with a factor of 1.8 between the first and second irradiation and read-out. In case B where the dosimeter was heated by read-out three times before the first irradiation, the high sensitivity is reached already at the first irradiation. After the initial increase there is only a slight change in sensitivity when irradiations are repeated with a constant dose.

Dependence on the temperature in the read-out oven. The temperature course in the read-out oven is plotted as a function of the position of the thermocouple along the transport path in Fig. 3. During the following measurements the temperature in the pre-heater oven was held at a constant level. After each irradiation the dosimeters were read twice; the first reading for different temperature levels in the read-out oven while the second reading was always performed at a temperature of 265°C. At the second reading the residual TL-light was recorded. The response at the first and

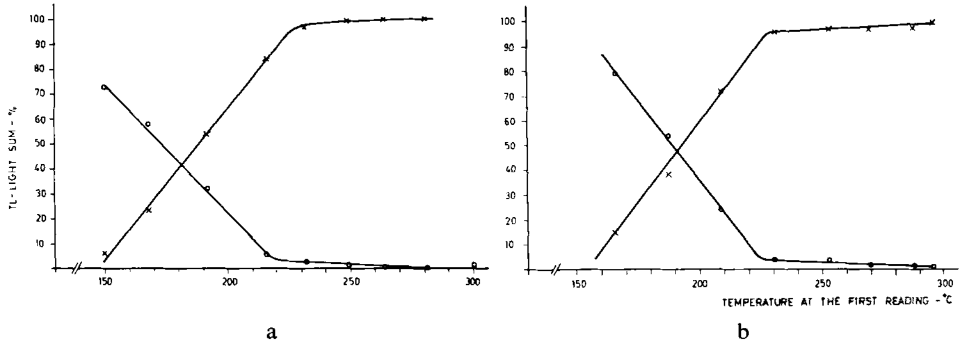

Fig. 4. TL-light sum as a function of the temperature in the read-out oven. The response is normalized to the last reading. a) Irradiation with 110 rad. Residual values at 265°C. b) Irradiation with 450 rad. Residual values at 290°C. The last residual value is read at 300°C. × first reading. ● second reading.

second reading is plotted in Fig. 4 a against the temperature in the read-out oven during the first reading. The dosimeter was irradiated with 110 rad. The TL-light sum is normalized to the last read-out. With the lowest temperatures the greatest emission of light was recorded during the second read-out but as the temperature increased a greater part of the signal was emitted during the first read-out. The residual value declines to less than 1 per cent, which is reached at 300°C. Corresponding curves for a reference temperature of 290°C and a dose level of 450 rad are illustrated in Fig. 4 b. The last value, which is read at 300°C, amounts to 1.5 per cent.

Dependence on the temperature in the pre-heater oven. The function of the pre-heater oven is to eliminate light emission from shallow traps in the dosimeters before they enter the read-out oven. The glow curve of LiF has five characteristic peaks, of which the three peaks emitted at the lowest temperatures have approximately the following half-lives at room temperature: 5 min, 10 hours and 1/2 year (ZIMMERMAN et coll). The light emitted in these three peaks is unsuitable for clinical dosimetry as the fading causes a dependence on the time between irradiation and reading. It should be expected that the response depicted as a function of the temperature in the pre-heater oven will appear as a plateau at the level where these three light peaks are eliminated since the two remaining peaks have considerably longer half-lives (approximatively 7 years and 80 years respectively at room temperature).

In order to obtain an idea of this temperature influence a dosimeter was irradiated and read repeatedly with successive increase of the temperature in the pre-heater oven. The time between irradiation and read-out was kept constant. The response normalized to the first reading is plotted in Fig. 5 as a function of temperature. As expected a tendency to a plateau appears between 90°C and 100°C. Further increase of the temperature in the pre-heater oven causes successive emptying of the stored energy which brings useful information on the absorbed dose received by the dosimeter material. The temperature of the pre-heater oven was set to 95°C during subsequent measurements.

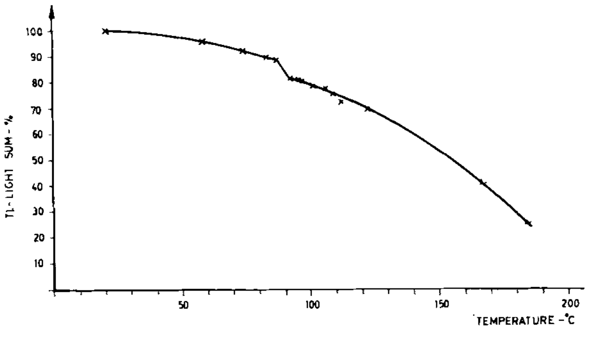

Fig. 5. Normalized TL-light sum plotted as a function of the temperature in the pre-heater oven.

Dependence on rate of transport. The transport rate of the measuring probes can be continuously varied between 0.5 and 1.2 mm per second. The response of a dosimeter repeatedly irradiated with 110 rad appears in Fig. 6 as a function of the rate, the reading temperature being 270°C. Two readings were performed. The second reading revealing the residual signal was always made at a rate of 0.9 mm per second; with rates between 0.6 and 1.1 mm per second a constant response was obtained. The rate of 1 mm^{-1} was used in the following, ensuring independence of small fluctuations in rate. The lowest curve in Fig. 6 illustrates the residual signal. The curve is rising with increasing rate but is still below 1 per cent at the rate of 1 mm s^{-1}.

Dependence on direction. The dosimeters exhibit dependence on the angle of incidence of the radiation in relation to the axial direction of the dosimeter. This effect was investigated by means of a perspex cylinder (5 cm diameter) in which three holes were bored at angles 0°, 45° and 90° to one another (Fig. 7). Measuring probes each containing one dosimeter (length 6 mm) surrounded by teflon spacers were inserted into the holes with the centre of the dosimeter in the centre of the cylinder. The cylinder was irradiated with 5 MV roentgen rays. The dependence of the response on the angle of incidence is given in Fig. 7. With axial irradiation of the dosimeter the reduction in response amounts to 7 per cent. Normally, the dosimeters are used with their axes approximately at right angles to the direction of the radiation beam.

Dependence on storage temperature. The temperature at which the dosimeters are stored will influence their sensitivity. This influence was determined for three different temperature levels: 4°, 22° and 100°C. Storage for up to 8 days at 4° and 22°C, respectively, did not cause any significant difference in sensitivity upon test irradiation. Storage at 100°C gave a reduction in sensitivity after 1 and 4 days of 50 and 75 per cent respectively.

Dependence of time lag between irradiation and read-out. A number of dosimeters were stored at room temperature for varying times after irradiation with 110 rad. Read-outs were performed after 0 to 116 hours. Immediately after read-out, the irradiation and read-out was repeated. The relative response defined as S/S_0, where S and S_0 are the sensitivities (rad^{-1}) in the first and second read-outs respectively, is given in the Table. There was no significant reduction after 116 hours, i.e. 5 days.

Table

Varying storage time between irradiation and reading

Storage time hours	Relative sensitivity S/S_0
0	1.00
1.5	0.99
3.5	0.99
6.5	0.99
16.5	1.03
20	1.00
46	1.02
49	1.01
64	1.04
116	1.00

Repeated irradiation with constant dose. Upon repeated irradiation with constant dose the dosimeters demonstrate an increasing sensitivity. The results of a number of irradiations with the absorbed dose of 450 rad appear in Fig. 8. The residual value was read after a varying number of measurements. The read-out temperature was 270°C. The gradual increase in sensitivity is due partly to the effects of irradiation and partly to the thermal treatment during read-out.

Repeated irradiation with varying doses. One dosimeter was irradiated repeatedly. First, with 10×110 rad, second, with 10×450 rad, and third, with 10×20 rad. The read-out temperature was 290°C. The sensitivity, normalized to the maximum sensitivity found, appears in Fig. 9. The response increases more rapidly for the high doses but tends to decline when changing over from high doses to series of low doses. The residual values, which were read between every tenth read-out, amount to less than 1 per cent.

Results of irradiations with doses of alternatively 20, 110 and 450 rad are plotted in Fig. 10 for two different dosimeters. The two dosimeters, which were read immediately after one another but were enclosed in different measuring probes, gave almost exactly the same results until the cycle was interrupted at read-out number 12, when one of the dosimeters was read without previous irradiation.

Discussion

The sensitivity of the LiF-teflon dosimeters was found to increase by a factor 1.8 after the first irradiation and read-out (Fig. 2). This change is due to thermally induced crystal defects which occur at high temperatures (ZIMMERMAN et coll). Rapid cooling to room temperature or lower makes this condition permanent, the high sensitivity persisting for a period of time depending on the storage temperature. CARLSSON (1969) investigated the influence of the thermal history on the thermoluminescence of LiF-teflon material. He pointed out that an appropriate heating process during read-out may satisfy the demands of both pre-annealing and cooling. He also found that

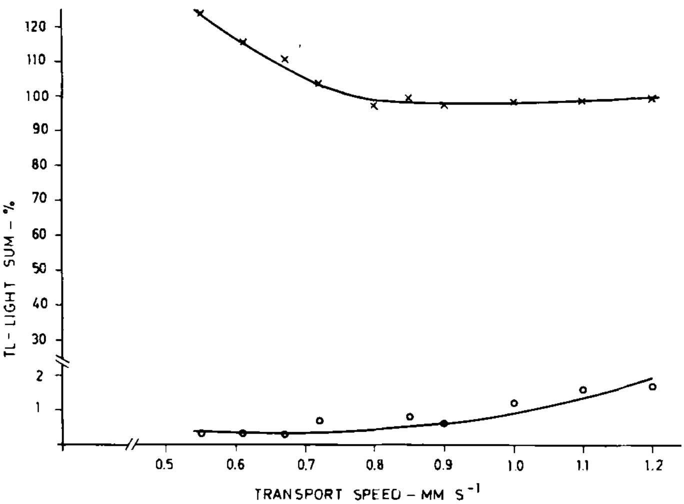

Fig. 6

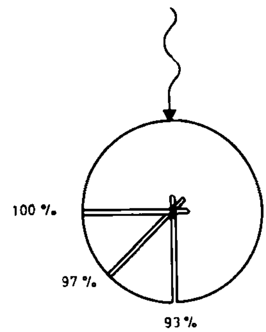

Fig. 7

Fig. 6. TL-light sum, normalized to last reading, plotted as a function of the transport rate. Residual values were read at a rate of 0.9 mm s^{-1}.

Fig. 7. Determination of the dependence on the angle of incidence of radiation in relation to the axial direction of the dosimeter. Relative response is given in percentage of the value at the angle of 90°.

after read-out at 300°C, storage at temperatures below 20°C for up to 10 days caused only slight reduction of sensitivity. Storage at temperatures above 50°C reduced the sensitivity, and more rapidly the higher the temperature was. On renewed read-out the thermal equilibrium in the dosimeter material was restored. If the dosimeter material was stored at the read-out temperature the thermal equilibrium was maintained and the sensitivity was kept constant. MÅRTENSSON (1969) found that high annealing temperatures decreased the precision of measurements.

The results mentioned above have been utilized by ALM-CARLSSON (1973) for precision measurements in connection with dosimetry at interfaces. In order to achieve the high level of precision of 0.3 per cent relative standard deviation the following precautions had to be taken: individual calibration of the dosimeters before every measurement, the cumulated dose had to be the same for all dosimeters irradiated in one group, correction had to be made for inadequate transparency of the teflon material, and heating other than in connection with read-out had to be avoided.

In clinical dosimetry a considerably lower level of precision can be accepted if the procedures can thereby be simplified. With the rapid and reproducible cooling after each read-out in the presented instrument it is possible to retain the high level of sensitivity which the dosimeters get in the high read-out temperature and utilize it for dosimetry. A high temperature gradient is obtained during exit from the read-out oven (Fig. 3). With a rate of transport of 1 mm per second the cooling rate will be approximatively 20°C s^{-1} and equally reproducible as the rate of rotation of the

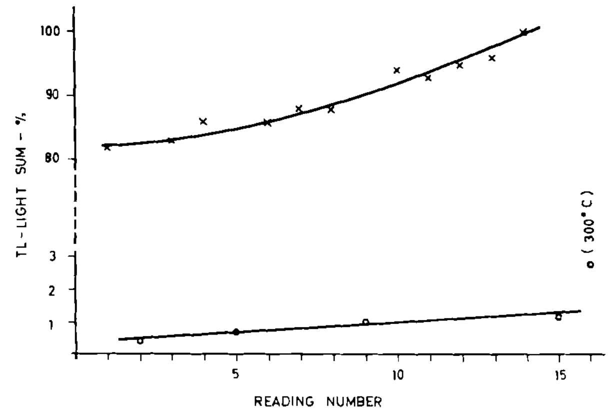

Fig. 8. TL-light sum for repeated irradiation and read-out of 450 rad. The response is normalized to reading number 14. Reading temperature 270°C. Residual values are illustrated by the lowest curve.

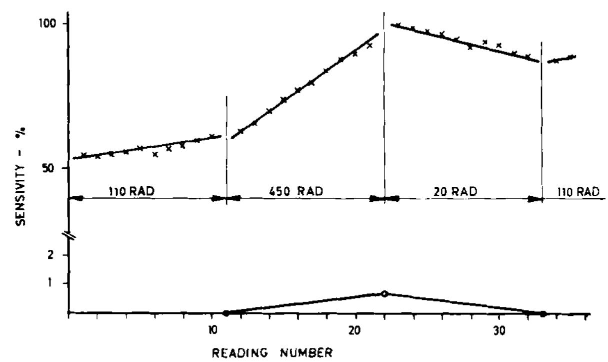

Fig. 9. Variation of sensitivity for repeated irradiation and read-out of 10 × 110 rad, 10 × 450 rad and 10 × 20 rad. Residual values are illustrated by the lowest curve. Reading temperature 290°C.

stepper motor. The cooling from 290°C to room temperature will take place within about 20 seconds.

The results presented in Figs 4, 6, 9 and 10 show that the sensitivity will increase with the number of read-outs and that complete release of trapped electrons in connection with read-out is not possible. To release all electrons a temperature of more than 300°C would be necessary inside the dosimeter, which would mean such high temperatures at the surface of the measuring probe as to damage it. It is therefore necessary to limit the temperature level to a maximum of 290°C determined as described above.

In repeated use including various radiation and thermal treatments the efficiency of thermoluminescent LiF will vary considerably (Figs 8–11). The efficiency variations are a result of the combined effects of radiation sensitization, radiation damage and thermal history. The sensitization is caused by non-luminescent deep traps with higher capture cross-section for electrons, than the luminescent traps (SUNTHARALINGAM 1968). As the non-luminescent traps are filled, more electrons will be captured by the luminescent traps resulting in an increased TL response. Suitable annealing procedures will restore the increased sensitivity to its initial level unless no radiation

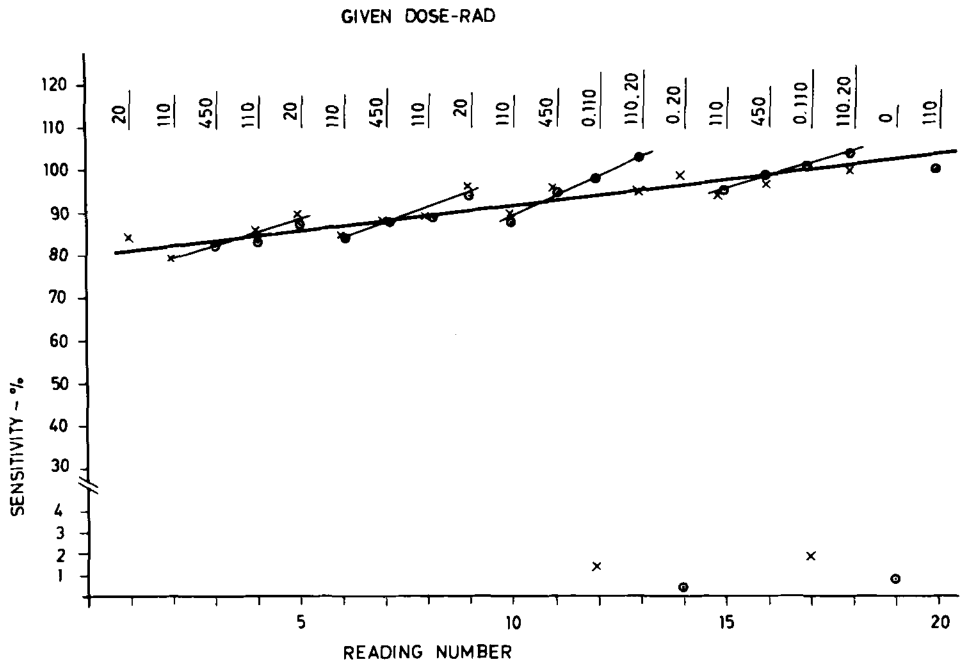

Fig. 10. Variation of sensitivity for repeated irradiation and read-out of varying doses. The two dosimeters are normalized to reading number 18 and 20 respectively. Reading temperature 290°C.

damage has occurred. There is, however, no threshold for radiation damage to LiF (CAMERON et coll. 1967) and this effect seems to be very difficult to repair.

During multiple irradiation and thermal treatment sessions the effect of radiation damage will be more marked than in one single irradiation and thermal treatment (CAMERON et coll. 1967). Combined effects of sensitization and damage was investigated by SPANNE & CARLSSON (1971). They concluded that both radiation sensitization and radiation damage seem to increase with increasing fractionation of irradiation and thermal treatment.

In the present dosimetry system the situation is further complicated by the rather great residual signal, which will depend strongly on the absorbed dose given in previous irradiations. Some of the luminescent traps will not be emptied during read-out but may partly be included in succeeding read-outs. This case is demonstrated in Fig. 9 where the sensitivity decreases by about 1 per cent at each read-out in the 20 rad irradiations, while it is increasing for doses of 110 rad and higher. Evidently it may be possible to choose the calibration dose so that an equilibrium of filled traps could be retained. Fig. 9 indicates that this calibration dose would be about 80 rad.

Method for the dosimeter measurements. Concluding the discussion above, the following method for using LiF-teflon dosimeters may be suggested:

the read-out should include a reproducible heating process with rapid cooling to room temperature,

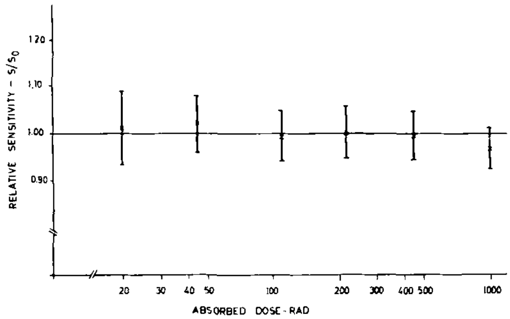

Fig. 11

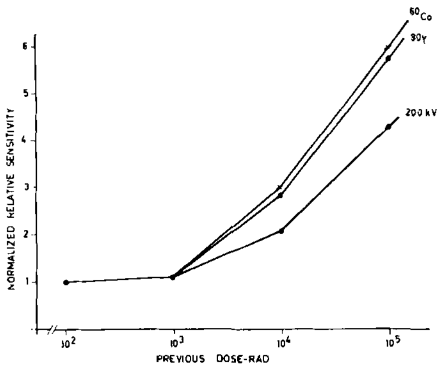

Fig. 12

Fig. 11. Relative sensitivity S/S_0, where S is the sensitivity (rad^{-1}) at an arbitrary reading and S_0 the sensitivity at the succeeding calibration with a dose of 110 rad. The dispersion is stated as two standard deviations.

Fig. 12. Relative sensitivity for a test dose of 100 rad of different radiation qualities as a function of pre-irradiation dose.

pre-annealing procedures at high temperature levels should be avoided,
post-annealing should be made to reduce fading at room temperature,
dosimeters should be stored in or below room temperature, and
dosimeters should be individually calibrated between measurements.

Obviously this schedule can be used with advantage only if the equipment and procedures are automated. In an automated measurement system, calibration of the dosimeters can be performed after each measurement without entailing excessive work. The calibration factor would reveal changes in the sensitivity of the dosimeter material. The output data must be obtained in a form suitable for computer handling with identification of individual dosimeters.

Calibration. The energy stored by the dosimeters when passing through the calibration radiation source with a certain speed will give a light-emission that reveals the sensitivity of the dosimeter material to the particles generated in or passing through the sensitive regions. The sensitivity to other radiation qualities or types of radiation may be different. The dosimeters should thus be calibrated for all qualities of radiation to be determined. The method presently used will be described as an example.

In general, calibration is based on one of the ^{60}Co therapy sources which is consistently used for continuous control of constancy for all dosimetric equipment in the laboratory. The measuring probes are irradiated with 100 rad ^{60}Co γ-radiation at the reference plane in a polystyrene phantom and read. Immediately thereafter, they are irradiated in the calibration radiation source (β-source) and read again. The rate of transport through the β-source is selected so that the response is of the same order of magnitude as the previous response to 100 rad from ^{60}Co. The whole procedure is repeated a number of times. When calculating the calibration dose the response for the succeeding irradiation with the β-source must always be used. The succeeding calibration will be performed subsequently for calculation of absorbed dose and it is essential that the procedures are identical.

The following symbols are used:

R_{Co} response to irradiation with 100 rad ^{60}Co gamma radiation
R_c response to succeeding irradiation with the β-source
R_x response to irradiation with radiation quality X
D_{Co} calibration dose received at transport through the β-source, according to the ^{60}Co measurement
D_x calibration dose received at transport through the β-source, according to measurement with radiation quality X.

The calibration dose for ^{60}Co γ-radiation during transport through the β-source is obtained by means of the expression

$$D_{Co} = \frac{1}{n} \sum_{i=1}^{n} \frac{R_c}{R_{Co}} \cdot 100,$$

where n is the number of times comparative measurements were performed.

A series of comparative measurements are then performed between each type of radiation and the β-source. With a dose of 100 rad given, the calibration dose is calculated from the expression

$$D_x = \frac{1}{n} \sum_{i=1}^{n} \frac{R_c}{R_x} \cdot 100.$$

Calculation of the absorbed dose is simplified in routine application if correction factors (C_x) are formed related to the ^{60}Co calibration according to

$$C_x = \frac{D_x}{D_{Co}}$$

Calculation of absorbed dose

During arbitrary measurements with radiation quality X the absorbed dose is calculated from the expression

$$D = \frac{R}{R_c} D_{Co} C_x$$

where R is the response to read-out of the measurement value.

During read-out the measurement values are automatically punched out on paper tape. The results are calculated and written out by means of a PDP 8/E minicomputer. Communication with the computer occurs via a Teletype. Data input to the computer is made by a paper tape reader, the values are stored in sequence in an input area. The calibration values are included on the same punched tape and in exactly the same order as the measurement values. The calibration values are fed in and simultaneously the absorbed dose is calculated and the result written out.

In routine use the procedure is that the computer first writes out the identification number of the measuring probe to be calculated and then asks for the correction factor C_x by writing, for example

5–21
C =

The operator writes out the appropriate factor and the computer then continues by asking for the tumour dose (TD) and reference dose (RD) by writing

TD = RD =

When these parameters have been allocated their values the result is written out for the whole measuring probe in the following table.

5–21
C = 1
TD = 235. RD = 200.

NR	Dose	%TD	%RD
1	200	85	100
2	205	87	103
3	190	81	95
4	170	72	85
5	140	60	70

The number (NR) is the number which identifies the individual dosimeter within the measuring probe.

The precision of the method of measurement is determined by the reproducibility of the sensitivity of the measuring instrument during read-out and succeeding calibration. If soiling of the optical system or other disturbances occur between the first and the second reading the results may be more or less erroneous. In order to check the sensitivity of the instrument during the two measurements, leader-probes containing a dosimeter of 18 mm length are used. The leader-probe is always irradiated with the calibration dose of 110 rad and placed first in the row of measuring probes to be read. The deviation between two consecutive readings with such a dosimeter and dose level is 1 per cent. The leader-probe may then be used as a monitor of the state of the instrument.

The methods used in the present dosimetry system diverge strongly from conventional systems. The effects included in repeated use of TLD will have an essential influence on the results. The reasons why radiation sensitization and damage increase with increasing fractionation of irradiation and thermal treatment are not satisfactorily understood. The phenomenon of sensitization and radiation damage should be investigated further.

Test of the method

Limits of error. Four measuring probes, each containing 9 dosimeters with the length of 6 mm, were submitted to different series of irradiations and read-outs with doses varying between 20 and 500 rad, and on one occasion 1 000 rad. Twenty-two irradiations were given, the cumulated dose being about 5 000 rad. Every other irradiation was a calibration irradiation with 110 rad. The relative sensitivity is defined as S/S_0, where S is the sensitivity (rad^{-1}) in a measurement and S_0 the sensitivity in the succeeding calibration. The relative sensitivity is plotted as a function of the absorbed dose (Fig. 11). The dispersion is stated with two standard deviations. The relationship between the sensitivity of an arbitrary dosimeter at the time of measurement and the sensitivity during the subsequent calibration irradiation will lie within the stated limits with 95 per cent probability. Between 100 and 500 rad the deviation from the value 1.0 ($S = S_0$) amounts to 6 per cent. For a dose of 20 rad the deviation increases to 9 per cent.

In situations in which repeated measurements can be performed or in which several measuring probes can be placed adjacent to one another the precision will be considerably increased. The automated read-out instrument and the availability of a computer for calculating and processing the results makes it possible to use a high number of dosimeters.

Dependence on LET. Induced LET dependence in LiF has been reported and discussed by SUNTHARALINGAM and CARLSSON & ALM-CARLSSON (1968). When dosimeters are irradiated with more than 10^3 rad this effect will be noticeable as the sensitivity will not increase as much for high LET particles as for low LET particles. The effect exerts a maximum influence at 10^5 rad. It is essential for the present method that the types of radiation measured have secondary charged particles of which the mean LET is equal to that of the beta particle spectrum in the calibration radiation source. The phenomenon itself can be utilized for comparing the LET of different types of radiation (CARLSSON & ALM-CARLSSON). The change in sensitivity of five measuring probes pre-treated with various absorbed doses from 10^2 to 10^5 rad is illustrated in Fig. 12. The deviation between ^{60}Co- γ and ^{90}Sr-^{90}Y-β irradiation lies within the errors of measurement, which indicates that the β-source can be used for calibration of high energy: roentgen rays, γ-rays and electron radiation; radiation qualities for which LET differs very little. The situation will be different for low energy photons. 200 kV radiation gives, for example 30 per cent lower relative sensitivity (Fig. 12) than ^{60}Co γ-radiation when dosimeters are pre-treated with 10^5 rad. When measurements are performed for this and other types of radiation with deviating LET, fresh dosimeters or dosimeters which have been calibrated recently for the type of radiation concerned must be used.

Acknowledgements

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SUMMARY

A radiothermoluminescence dosimetry system based on an automated reader has been developed. The system utilizes the high sensitivity of the dosimeter material after heating. Thermal treatment is limited to the temperature process in connection with read-out. The measurement values are punched out automatically on paper tape and calculations performed by means of a minicomputer PDP 8/E. The dosimetric system meets the needs of routine use in clinical environment. Recommendations for the practical use of the system are given.

ZUSAMMENFASSUNG

Es wurde ein Strahlenthermoluminiszens-Dosimeter-System, das auf einem automatischen Leser aufbaut, entwickelt. Das System macht von der hohen Empfindlichkeit des Dosimetermaterials nach Erwärmung Gebrauch. Die Wärmebehandlung ist auf die Temperaturprozesse im Zusammenhang mit der Ablesung beschränkt. Die Messwerte werden automatisch auf einem Papierstreifen gestanzt und die Berechnungen mit dem Minikomputer PDP 8/E ausgeführt. Das dosimetrische System füllt die Forderungen der routinemässigen Verwendung unter klinischen Bedingungen. Ratschläge für den praktischen Gebrauch des Systems werden gegeben.

RÉSUMÉ

L'auteur a mis au point un système de dosimétrie par radiothermoluminescence basé sur un lecteur automatique. Ce système utilise la haute sensibilité du matériel dosimétrique après chauffage. Le traitement thermique est limité au chauffage au cours de la lecture. Les résultats de mesure sont transcrits automatiquement en perforations sur une bande de papier et les calculs sont faits au moyen d'un miniordinateur PDP 8/E. Ce système dosimétrique répond aux besoins ordinaires dans l'usage clinique. L'auteur fait des recommandations pour l'utilisation pratique de ce système.

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