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A European quality assurance network for radiotherapy: dose measurement procedure

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Abstract. In the frame of the experimental implementation of a European quality assurance network for external radiotherapy, the methodology in the European Measuring Centre (MC) is presented. Mailed TL dosimeters are used for the check of the beam output and of the beam quality of photon beams. The thermoluminescent material is PTL 717 LiF powder. The readings were first performed on a manual, and then on an automatic reader, with standard deviations of the mean of 0.7% for one dosimeter. Corrections for supralinearity and for the energy dependence of the dosimeter response are applied. An original method has been developed to correct for the variation of the LiF response as a function of time. It is shown that the sensitivity of the powder changes during storage, leading to a kind of 'inverse fading'. The global uncertainty of the TL postal measurement procedure is estimated to be about 1.5% for the ^{60}Co beams and 2% for the x-ray beams. Intercomparisons with the IAEA and with the EORTC have shown an agreement better than 2% for all energies. It can be concluded that the results of the MC are suitable for the requirements of a European quality assurance network.

1. Introduction

An experimental quality assurance network for external radiotherapy, sponsored by the EC committee 'Europe Against Cancer', was set up in 1992. Its aim is to allow any European centre to be connected to a structure involving both a national structure and the European coordination and measurement centres. Previously, the quality assurance programmes existing in some European countries were carried out at a national level (Davis and Faessler 1993, Hoornaert *et al* 1993, Johansson *et al* 1982, Thwaites *et al* 1992, Wittkämper and Mijnheer 1993), apart from the IAEA postal service (Svensson *et al* 1990, 1993, Svensson and Zsdansky 1994) and the EORTC audits for research centres (Hansson and Johansson 1991). The European dimension of the EC network presents the advantage of allowing a homogenization of the protocols used for quality assurance in all the European countries. The project includes the check of the beam output and the beam quality in reference conditions, the verification of other beam data and the dose calculation procedure with a multipurpose phantom, and finally *in vivo* dosimetry at the individual patient with mailed dosimeters.

The European Measuring Centre (MC)§ is responsible for the technical study, the optimization of the measurement methodology and techniques, and of all the measurements performed for the checks of the participating centres, in relation with the European Coordinating Centre (CC)‖.

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The details of the organization and the first results concerning the check of the beam output and the beam quality of photon beams have been presented in previous publications (Derreumaux *et al* 1993, Dutreix *et al* 1993, 1994). This paper deals with the methodology derived from the IAEA/WHO experience and the technical aspects of the dose measurements performed in the MC during the first part of the implementation of the project. At the present time, 162 photon beams (58 ^{60}Co and 104 x-ray beams) from 85 centres have been checked, corresponding to more than 2000 thermoluminescence dosimetry (TLD) readings.

The choice of the thermoluminescence (TL) material, the reading procedure, the calibrations, and irradiation conditions in the measuring centre will be presented and discussed.

2. Materials and TL reading methods

2.1. Choice of the TL material

TL postal dosimetry has been chosen to perform the measurements as it has already proved its suitability for such wide quality assurance programmes (Bridier *et al* 1994, Hansson and Johansson 1991, Kirby *et al* 1986, Svensson *et al* 1990).

As other authors, the Institut Gustave Roussy (IGR) has chosen LiF as the TL material, considering its effective atomic number ($Z_{\text{eff,LiF}} = 8.14$), which makes it close to tissue equivalence ($Z_{\text{eff,tissue}} = 7.42$) for the high-energy beams used in radiotherapy. Its low fading is an important characteristic for mailed dosimeters as they are exposed to ambient temperatures during travel (Cameron *et al* 1968, Bridier *et al* 1994, McKeever 1985).

The LiF used is PTL 717 (Desmarquest-CEC, Evreux, France). This powder is doped with Mg, Ti, and Na, and enriched in ^{7}Li. It presents interesting features, including an especially low fading, typically less than 5% per year at room temperature, associated with a favourable repartition of the dosimetric information in the glow curve (Portal 1978). In particular, one observes a strong reduction of peaks III and IV in this glow curve, as compared to the glow curve of the Harshaw LiF TLD 700 (figure 1). The reduction of the peaks III and IV allows an easier separation of the unstable low-temperature peaks (I, II, and III) from the dosimetric peaks (IV and V) during the heating procedure, and improves the repeatability of the readings.

The PTL 717 enrichment in ^{7}Li (99.95%) aims to avoid the capture nuclear reaction between ^{6}Li and thermal neutrons: $^6\text{Li} + \text{n} \rightarrow {}^4\text{He}(\alpha) + {}^3\text{H}$ (McKeever 1985), as the photon beam qualities commonly used in high-energy external radiotherapy range from the ^{60}Co γ-rays to 25 MV x-rays. Photoneutrons are produced by (γ, n) reactions in the heads of accelerators when photon energies above 10 MeV are emitted (Palta *et al* 1984).

The choice of powdered TL material, instead of solid chips or rods, is justified by the great precision that must be reached for quality controls (a precision better than 2% ($1s$) on the measured dose requires a standard deviation of the TL readings of 1.5% or less (Kirby *et al* 1992)). In addition, if a batch of powder is well mixed and sifted after each thermal annealing, the homogeneity of the powder allows the calibration to be performed from a small sample of the batch. In contrast, to reach such a precision, solid dosimeters should be calibrated individually and regularly, to take into account any drift of the relative sensitivities of the individual dosimeters with time. The advantage of using powder is emphasized by the fact that, with the new reading methodology, which will be described below, the importance of weighing the samples before reading is minimized.

The thermal annealing consists of heating the powder up to 500 °C in an oven for 4 h and then cooling it quickly by projection on a heat conductive surface at ambient temperature.

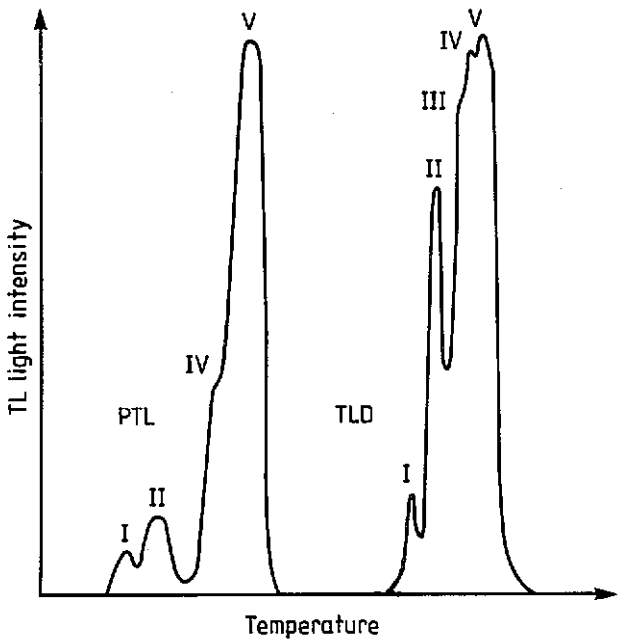

Figure 1. A comparison of the TLD 700 and PTL 717 glow curves (after Portal 1978). The peak III of the PTL glow curve is very weak and cannot be distinguished.

Some grains splinter during annealing, and as the dosimetric characteristics of a given batch of powder depend on the grain size, a systematic sifting is carried out after annealing to eliminate the smallest grains (diameters below about 70 μm).

The powder is contained in opaque cylindrical polyethylene capsules identical to those used by the IAEA. The wall thickness is 1 mm, and the internal length and diameter are 16 mm and 3 mm respectively. Each capsule contains about 160 mg of powder, allowing five readings per point of measurement (about 30 mg per reading).

As explained below, the dosimeters can be irradiated in water. If the powder is damp, the grains aggregate and make the readings uncertain. So, to make the containers water tight, a suitable glue is used around the cap.

2.2. Reading procedure

2.2.1. Manual reading. During the first two years of the European Network setting up, the readings were made on a Saphymo LDT 21 manual reader.

The powder is poured on a metallic tray heated by the Joule effect. The heating cycle consists of a preheating at 130 °C for 6 s, followed by a linear increase of the temperature, of about 8 °C s^{-1}, to a maximum of 260 °C. The signal is integrated during the second heating step, lasting 16 s.

The photocathode of the photomultiplier (type 9526 S EMI) presents a spectral response curve centred around 400 nm. This fits with the wavelengths of the light emission of LiF:Mg,Ti,Na (Portal 1981). A chromatic filter MTO ATERVEX Ta-1 is placed in front of the photomultiplier window to remove infrared and red radiations due to black body emission of the oven components.

The measurements are made in a steady nitrogen flux of about 3.5 l min^{-1}, to avoid spurious thermoluminescence due for instance to the presence of oxygen, tribothermoluminescence, or the burning of dust particles (Svarcer and Fowler 1967).

The TL response of a sample of powder is at first dependent on the mass of powder, so each sample is weighed with high-precision scales (sensitivity 0.01 mg). Readings are made with samples of masses ranging between 29.7 mg and 30.3 mg (30 mg$\pm$1%). In this range, the quantity of powder is sufficient to cover the whole area of the heating plaque, removing a notable part of the black body emission from the metallic plaque, and the thickness of the sample is small enough to avoid significant self-absorption. The TL response is close to a linear function of the mass, and is corrected for. All the readings are normalized to the reading for 30.00 mg.

2.2.2. *Automatic reading.* A 'PCL3' automatic reader is now used to perform the routine measurements. It allows the reading of TL material to be made with not only solid chips, microrods, or pellets, but also powder. It has been developed at the Commissariat à l'Energie Atomique and is manufactured by Fimel (Vélizy, France) (Barthe *et al* 1990, Marinello *et al* 1992). The powder is poured into small containers made of stainless steel. The containers are placed in a loader with a capacity of about 90 containers. The preheating and the heating are carried out through automatic motion of the containers, one by one, allowing successive stays of each container on the surface of the two ovens.

The ovens are heated by the Joule effect. Their temperature is kept constant, thanks to a monitoring thermocouple. The reading parameters have been optimized to reach the best repeatability of the readings, with a fading as low as possible (elimination of the unstable low-temperature peaks thanks to the preheating). For preheating and heating, the ovens are brought to temperatures of 130 °C and 400 °C. The containers stay for 10 s on each oven, with a pause of 5 s in an intermediate position at room temperature.

A steady nitrogen flux of 3.2 l min^{-1} is used. The light emitted by the TL material is measured with a Hamamatsu R 268 photomultiplier (PM). An MTO 415 nm chromatic filter is placed in front of the PM window to fit the detection system spectral characteristics with the LiF light emission. Additional MTO 1 and 2 attenuator filters (10$\times$ and 100$\times$) can be used according to the dose range. It is thus possible to read with a good precision doses ranging from 1 μGy to more than 10 Gy.

The powder is poured into the containers with a manual dispenser, without weighing. Each container receives about 30.5 mg, with a precision of $1s = 0.3\%$.

It appears that with such heating conditions, in particular the use of a thick layer of powder, the response becomes much less dependent on the weight (autoabsorption).

3. Dose measurement methods

3.1. Calibration at the measuring centre

TLD is a relative dosimetry. The dose is determined by comparing the response of a given dosimeter to the response of a reference dosimeter, which has been irradiated at a point where the dose is precisely known. At the IGR, the reference dosimeters are irradiated at 2.00 Gy in a ^{60}Co beam, using a specially designed device. It consists of a homogeneous parallelipipedic Perspex phantom, which can be accurately fixed to the collimator of the Theratron 780 unit, and in which a dosimeter can be irradiated in reproducible conditions. The centre of the dosimeter is situated at 5 cm depth, at 80 cm from the ^{60}Co source. The irradiation field (15$\times$15 cm^2) is homogeneous over the whole section of the sensitive volume

of the dosimeter. The dose is determined by measurement with the reference ionization chamber of the IGR radiotherapy department, an NE 2571 chamber (0.6 cm^3) connected to a Therados RDM 1S electrometer, which can be introduced into the reference device in place of the LiF dosimeter. The determination of the dose is made following the IAEA protocol (IAEA 1987). The measurement chain (chamber + electrometer) is calibrated every three years at the Laboratoire de Mesure des Rayonnements Ionisants (LMRI, Saclay, France), SSDL, and the calibration factor is traceable to the Laboratoire Primaire des Rayonnements Ionisants (LPRI, Saclay, France), PSDL, with an agreement better than 1%.

For routine use, the irradiation time is determined with a calculation taking into account the ^{60}Co source decay.

3.2. Study of the measurement chain characteristics

The TL response is not necessarily a linear function of the absorbed dose, and depends on the beam quality and on the time elapsed after the irradiation. So, if a dosimeter is irradiated in conditions different from the conditions in which the reference dosimeter is calibrated, for instance in another beam quality, at a different dose, at a different time, correction factors must be applied to determine the absorbed dose.

Measurements have been performed to determine the values of the correction factors as a function of the absorbed dose, the beam energy and the delay after the irradiation. The readings of the TL response were made both on the Saphymo and on the PCL3 readers.

As far as the variation of the response with time is concerned, as presented below, we did not observe the thermal fading usually described in the literature, i.e. a systematic decrease of the response due to the thermodynamic release of trapped charges, but we often found an increase of the response with time. This led us to introduce a more general term than fading: the 'delayed response alteration' (DRA).

In the current practice, the TL dosimeters are mailed to the participating centres in expanded polystyrene boxes in order to minimize the DRA, possibly linked to large variations of the ambient temperature, as any precise estimation of the DRA occurring during the travel can only be made if the dosimeters are kept in conditions close to the laboratory conditions.

3.3. The operational phase

3.3.1. Reference and monitoring dosimeters. The delay between the dosimeter preparation and the dosimeter reading is, as a mean, one and a half months, and can reach two months. Undesirable and unpredictable events may occur, such as accidental irradiations or, in contrast, accidental DRA. When the dosimeters are sent to a given participating centre, four supplementary dosimeters, called 'A', 'B', 'C' and 'D', are used to monitor their 'history' (table 1). The dosimeters 'B', 'C' and 'D' are used to estimate the DRA. They are irradiated at 2 Gy at the MC, in a ^{60}Co beam, in the reference Perspex device presented above. 'C' is irradiated on the day of the dosimeter mailing, and stays at the MC. 'D' is irradiated 3 d before reading at the MC. 'D' is the reference dosimeter. A comparison of the readings of 'C' and 'D' allows the estimation of the DRA occurring during the travelling period of the dosimeters, in the laboratory conditions. 'B' is irradiated at the same time as 'C', but travels with the dosimeters. 'B' allows the detection and estimation of any unexpected DRA, due for instance to a long exposure to excessive heat.

The dosimeter 'A' is irradiated neither at the MC nor in the participating centre, and is joined to the mailed dosimeters. It is used to measure an unexpected irradiation, caused for instance by the vicinity of a radioactive source, or in the treatment room during the irradiation of other dosimeters, or by any x-ray exposition occurring at the customs.

Table 1. Reference and monitoring dosimeters. 'B', 'C' and 'D' are irradiated at 2 Gy in a ^{60}Co beam.

Dosimeter	Irradiation	'History'	Aim
A	Not irradiated	Mailed with the dosimeters	Measurement of an unexpected irradiation
B	On the day of dosimeters mailing	Mailed with the dosimeters	Estimation of the DRA for mailing conditions
C	On the day of dosimeters mailing	Remains at IGR	Measurement of the DRA in the laboratory conditions
D	On the day of dosimeters reception. About 3 d before reading	Remains at IGR	Reference dosimeter

All the dosimeters involved in the check of a participating centre ('A', 'B', 'C', 'D', and the ones irradiated by the centre) contain TL powder from the same batch of powder, i.e. all the powder used for a given centre is homogeneous. The reason for that procedure is that, in our experience, the powder sensitivity changes with time as a function of the number of irradiations and annealing cycles, and of the time elapsed after the last annealing.

In order to improve the precision of the TL measurements, the readings are made at least 24 h, and if possible 3 d, after the irradiation. It appears that the DRA may not be reproducible during the hours following the irradiation. It seems that significant transfers of charge from one trap to another occur in the LiF crystals after the irradiation. Moreover, the repeatability of the readings improves as the TL material stabilizes during the few days after the irradiation.

3.4. Irradiation at the participating centre

3.4.1. The experimental set-up. The dosimeters are irradiated in a water phantom. They are perpendicularly inserted in a vertical cylindrical hollow Perspex support, stabilized in water by a plastic disc base (figure 2). This support is the same as the one used by the IAEA for the Agency International Quality Assurance Programme (Svensson *et al* 1990, 1993). This device allows an easy, quick, precise, and reproducible positioning of the dosimeters in the water phantom, at different depths (5, 7, 10, and 20 cm) corresponding to the reference depths recommended by the various national and international protocols. The IAEA protocol, for instance, recommends 5 cm or 10 cm for the measurement of the absorbed dose as a function of the beam quality (IAEA 1987), while the SEFM Spanish protocol recommends 5, 7, or 10 cm with increasing energy.

3.4.2. The beam output check. For the beam output check, two dosimeters must be irradiated successively at 2 Gy in a vertical beam, at the depth of reference, in a 10 cm × 10 cm field and at the source to surface distance or source to axis distance normally used in the centre.

Each centre is required to check the beam calibration with an ionization chamber irradiated in the same geometrical conditions immediately before the irradiation of the TL dosimeters.

3.4.3. The check of the beam quality. According to the IAEA protocol (IAEA 1987), two quantities may be used as quality indices of x-ray beams: the ratio QI of the doses (or of the tissue–phantom ratios) at 20 cm and 10 cm depth, for a constant source–detector distance and a 10 cm × 10 cm field at the plane of the detector (QI), and the ratio D_{20}/D_{10} of the doses measured at 20 cm and 10 cm depth, at a 100 cm source to surface distance and for a 10 cm × 10 cm field at the phantom surface (QI*).

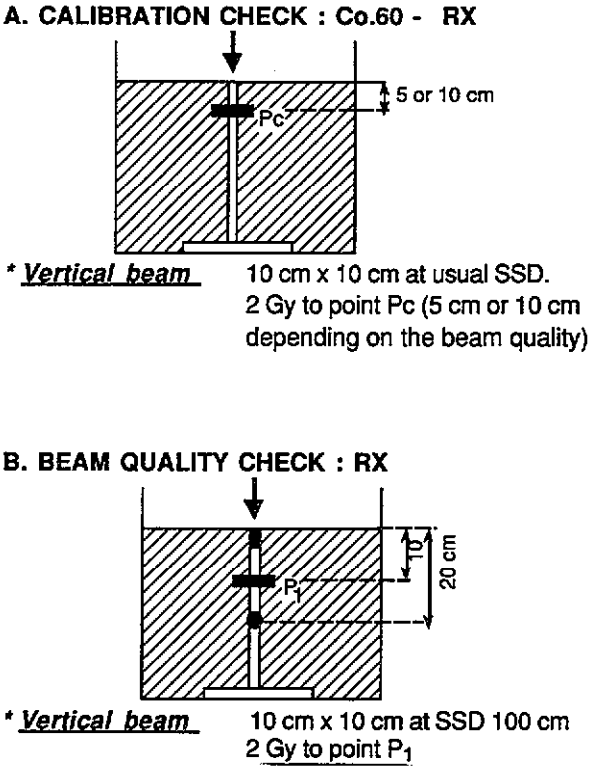

Figure 2. The irradiation procedure for the check of the beam output and beam quality of the photon beams. The LiF dosimeters are irradiated in a water phantom, with a Perspex support identical to the one used by the IAEA.

In the European Network, the quantity QI* is measured to check the beam quality of the x-ray beams. Two TL dosimeters are irradiated simultaneously at depths of 10 and 20 cm, in the reference conditions (100 cm source to surface distance, 10 cm × 10 cm field), with a dose of about 2 Gy to the upper one. The ratio of the dose at 20 cm depth and the dose at 10 cm depth gives the measured value of QI*. The two dosimeters irradiated simultaneously are perpendicular to each other, to reduce the shadowing effect of the upper dosimeter on the lower one.

3.5. Dose calculation at the measuring centre

The absorbed dose to water at the point corresponding to the geometrical centre of a TL dosimeter, D_m, is obtained from the reading of n samples of its powder using the following expression:

$$D_m = [(M - A)/R]2C_D C_E C_T$$

where M is the mean of the readings of n samples of LiF powder contained in the dosimeter, after substraction of the electronic background and correction for the drift of the reader, A is the mean of the readings for the dosimeter 'A', R is the mean reading for the reference dosimeter 'D', C_D is the correction for the non-linearity of the dosimeter response as a

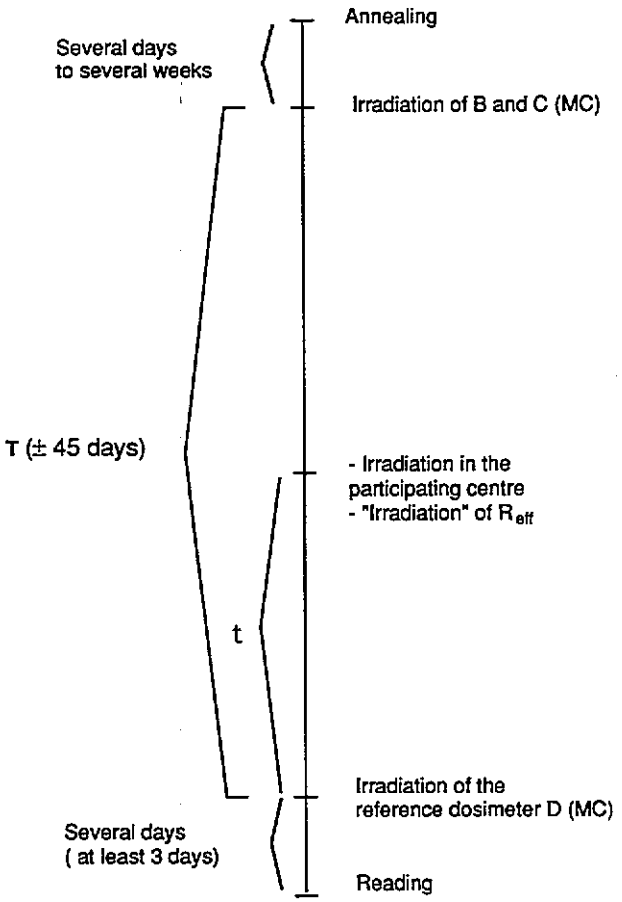

Figure 3. The 'history' of the TL dosimeters used for a mailed check in a participating centre. B, C, D, and R_{eff} are defined and their role is explained in the text.

function of the absorbed dose in water, C_E is the correction for the variation of the dosimeter response as a function of the beam energy, and C_T is the correction for the DRA with time.

$$C_T = R/R_{eff}$$

where R_{eff} would be the mean reading of a fictive 'effective reference' dosimeter, i.e. a dosimeter that would be irradiated in the reference conditions (2 Gy, ^{60}Co, in the MC special device) at the same time as the dosimeters irradiated in the participating centre, and that would have the same history (same DRA) (figure 3). R_{eff} can be estimated through the weighted average of the mean readings of the dosimeters B, C, and D with the equation

$$R_{eff} = \{[(B - A) + C]/2\}t/T + D(T - t)/T$$

where B, C, and D are the mean readings of the dosimeters B, C, and D, respectively, t is the time elapsed between the irradiation of the dosimeters in the participating centre and the irradiation of D in the MC, and T is the time elapsed between the irradiation of B and C and the irradiation of D, in the MC.

The following hypothesis are assumed.

(i) The DRA may be approximated by a linear function of the time (or a summation of linear functions) over the considered period of time (at least 3 d and a maximum of two months between the irradiation and the reading of every dosimeter).

(ii) If an accidental irradiation is detected with A, it has probably affected all the mailed dosimeters, including B, and B must be corrected for.

(iii) If an accidental DRA is measured with B, one does not know whether the other mailed dosimeters have also undergone it (for instance, an excessive DRA due to a momentary exposure to high temperature would also affect the other dosimeters if it occurred after their irradiation, and would not if it occurred before). The probability that the other dosimeters are also affected by the accidental DRA is assumed to be 0.5, and the corresponding correction of the dosimeters readings is taken as half the DRA value measured with B by taking into consideration the average value of $(B - A)$ and C.

For the check of the beam ouput, the mean of the doses measured at the MC for the two irradiated dosimeters, D_m, is compared to the dose stated by the participating centre, D_s. Regarding the check of the x-ray beam quality, the measured ratio QI^*_m is compared to the corresponding ratio stated by the centre, QI^*_s.

If the centre provides us with the quality index QI (TPR20/TPR10) of a given x-ray beam instead of QI^*, we derive the value of QI^*_s using the table of Andreo, published in *IAEA Report 277* (IAEA 1987), relating QI^* to QI for the whole range of beam qualities encountered in radiotherapy.

3.6. Traceability of the measurements to SSDL

The TL postal dosimetry methodology of the MC is regularly checked by internal quality controls and external audits.

The reproducibility of the ^{60}Co reference dose is monitored with the reference ionization chamber calibrated in the LMRI (Saclay, France), SSDL of France.

The reproducibility of the TL calibration curves (dose and energy responses) is tested at least every year.

External checks have been regularly made by intercomparison with the EORTC and the IAEA, acting as SSDLs. Checks of the calibration of the MC beams (^{60}Co, 4 MV, 10 MV, 18 MV, and 25 MV x-ray beams) were performed by irradiating, at the MC, TL dosimeters to a given dose (2 Gy). The dosimeters were prepared and read by the EORTC or the IAEA. The irradiations are performed in a water phantom, in geometrical reference conditions, after a check of the beam calibration with the MC reference ionization chamber.

The whole TL postal dosimetry methodology is checked by sending TL dosimeters to the IAEA for irradiation at about 2 Gy in reference conditions, and by comparing the value of the dose stated by the IAEA to the dose measured at the MC.

4. Results

4.1. Uncertainties due to the procedure

The uncertainties can include random or systematic uncertainties. The first paragraphs deal with the estimation of the random uncertainties. The last paragraph deals with the external audits, intended to detect the possible systematic uncertainties.

per dosimeter on the Saphymo reader and of five samples on the PCL3 reader involves a standard deviation of the mean value ($1s/\sqrt{n}$) of about 0.7%, corresponding to one point of measurement.

A drift of 1–3% is commonly observed on both the readers when a long series of readings is performed (about 15 dosimeters), and is corrected for. For both the readers, the electronic background signal (without infrared emission) can be reduced to a value smaller than 0.1% of the TL signal, corresponding to a dose of the order of 2 Gy.

4.1.2. Random uncertainties in measurements. A quadratic sum of the random uncertainties for all the factors entering in the dose calculation (reference dose, reading of a given dosimeter, reading of the reference dosimeter, and correction factors C_D, C_E and C_T) leads to an estimation of the global uncertainty for the TL postal measurement procedure of about 1.5% and 2% ($1s$) for the measurement of the beam output of a ^{60}Co beam and of an x-ray beam, respectively. This is in agreement with the estimation by Kirby *et al* (1992) of the precision of postal measurements with TL dosimeters.

Regarding the measurement of the beam quality of an x-ray beam, the quadratic sum of the uncertainties for the readings of the two dosimeters (10 and 20 cm depths) and for the correction factor C_D results in a global $1s$ value of 1%.

The postal measurements performed in the frame of the EC Network provide values supporting the estimation of the precision of the MC measurement methodology. If one considers the centres where an external audit has been performed during the five years preceding the EC check by a national or an international organization, centres A of the EC Network (Dutreix *et al* 1993, 1994), one can expect a standard deviation only slightly higher than the standard deviation due to the method alone. In the data for the 60 centres A checked from March 1992 to March 1994, the standard deviations of the ratios D_m/D_s are 1.9% and 2.0% for the ^{60}Co beams ($n = 15$) and for the x-ray beams ($n = 45$), respectively (figure 4). The standard deviation of the ratios QI^*_m/QI^*_s ($n = 42$) is 1.8%. These uncertainty values include not only the uncertainties on the dose determination, but also the uncertainties linked to the set-up of the phantom and to the determination of depth doses in the participating centres, and to possible systematic errors in our methodology.

4.1.3. Intercomparisons. Between 1991 and 1993, four intercomparisons have been carried out with the EORTC and the IAEA (table 2). In these intercomparisons (^{60}Co, 4 MV, 10 MV, 18 MV, and 25 MV x-rays), the agreement between the MC stated dose and the measured dose was better than 2% for all photon beams and for all intercomparisons.

Table 2. Results of the TLD intercomparisons with the EORTC and the IAEA. The dosimeters were irradiated in a water phantom and in reference conditions (on axis, 5 or 10 cm depth, 10 cm × 10 cm field, at usual source to axis or source to skin distance).

	EORTC/IGR		IAEA/IGR	
Beam quality	1991 D_m,EORTC/D_s,IGR	1992 D_m,IAEA/D_s,IGR	1992 D_m,IGR/D_s,IAEA	1993 D_m,IAEA/D_s,IGR
^{60}Co	0.995	0.992	1.009	0.982
RX 4 MV	1.00	0.984		
RX 18 MV	0.99	0.989		
RX 25 MV	0.995			

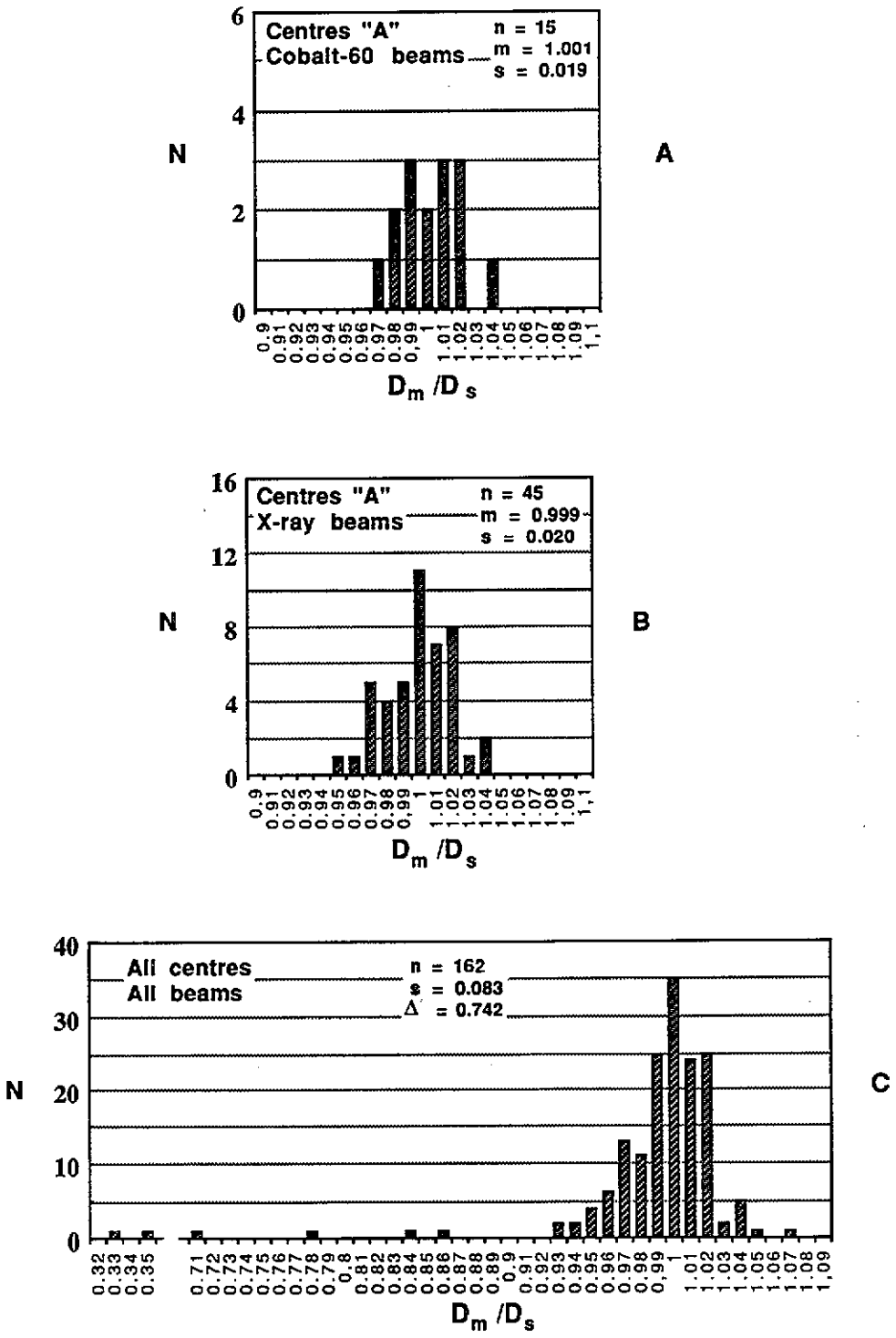

Figure 4. Distributions of the deviations for the beam output checks for ^{60}Co beams (A) and x-ray beams (B) of 'A' centres, and for all beams of all centres (C). n is the number of beams, s the estimation of the standard deviation, m the mean, and D the spread.

In 1992, the MC sent dosimeters to be irradiated at the IAEA for a check of the global EC TL dosimetry, and the agreement was better than 1% ($D_m/D_s = 0.992$).

4.2. Response curves

4.2.1. Delayed response alteration (DRA). The DRA was investigated through both specific measurements and data resulting from the series of measurements performed in the frame of the postal checks. Concerning the specific measurements, the procedure consisted of irradiating dosimeters at 2 Gy in the ^{60}Co beam, on different days over a long period of time (one month or two), and by reading all the TL dosimeters at the end of the given period. The variation of the response observed as a function of the delay between irradiation and reading is presented as a DRA curve in the laboratory stockage conditions (temperature = 25 °C).

Several experiments have been performed, and it appears that, as quoted above, we often observe a varying behaviour of the TL material between irradiation and reading, obviously leading to different curves. Furthermore, the variation is not necessarily a decrease of the reading as the delay between irradiation and reading increases, especially for long-term readings (figure 5). Observing the whole set of data obtained from the readings of dosimeters C and D in the checks with participating centres in our two months observation time, a large proportion of increases of the response appears when large delays occur between irradiation and reading (figure 5). The mean increase is about 2% for a two months delay.

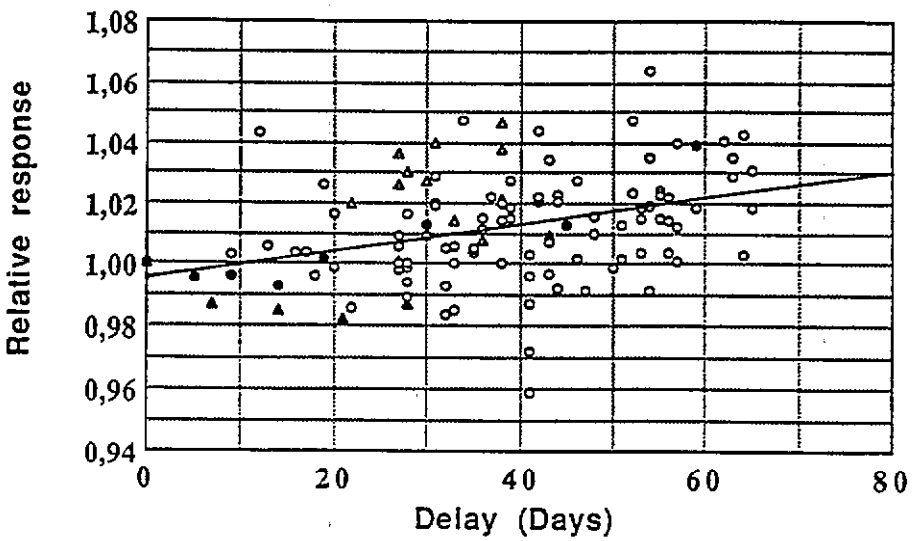

Figure 5. The variation of the LiF response as a function of the delay after the irradiation, in the laboratory conditions ($t^0 = 25$ °C). Each response is normalized to the response of the reference dosimeter, read a few days after the irradiation. The circles concern the measurements made with the Saphymo manual reader, while the triangles refer to the measurements with the PCL3 automatic reader. The white circles and triangles correspond to the data from the postal measurements, and are the ratios C/D of the reading of the dosimeter 'C' to the reading of the dosimeter 'D'. These points correspond to different batches of powder, with different delays between the annealing and the irradiation. The black circles and triangles concern the specific DRA measurements performed at the IGR, leading to different 'DRA curves'. Each curve is obtained with powder extracted from the same batch of powder.

This apparently complex behaviour of the LiF response as a function of time cannot be explained by the measurement uncertainties ($1s = 1\%$). It is generally assumed that the DRA is a function of the time elapsed after the irradiation. The large spread of the results seems to indicate that it is also a function of some other parameter(s), such as the time elapsed between the annealing and the irradiation of the powder.

An estimated correction factor for the DRA, C_T, measured for each TL postal check with the dosimeters B, C, and D, has systematically been applied for the calculation of the dose, whatever its value and even if it is less than unity ($C_T < 1$ means that the LiF response has increased with the time elapsed between dosimeter irradiation and dosimeter reading; this is a kind of 'inverse fading').

The DRA observed with the dosimeters mailed for the EC checks has commonly been found in the range 0–2.5%, and was always smaller than 5%, except once, whatever the delay and the stockage conditions.

4.2.2. Dose response. To study the dosimeter response as a function of the absorbed dose to water, the dosimeters have been irradiated in a ^{60}Co beam, in the dedicated reference Perspex device, at doses ranging from 0.2–10 Gy.

The dosimeter response curve as a function of the absorbed dose is supralinear in the dose range 0.5–10 Gy. In the measuring conditions, the sensitivity (reading/absorbed dose) increases linearly by 0.6% Gy^{-1} and 0.5% Gy^{-1} on the Saphymo and on the PCL3 readers, respectively (figure 6).

4.2.3. Energy response. The energy response curve has been determined for the typical photon beam qualities encountered in radiotherapy, i.e. from a ^{60}Co γ-beam to a 25 MV x-ray beam. Five beam qualities are available at the measurement centre, from four treatment units: a ^{60}Co γ-beam from a Theratron 780 unit, and 4 MV, 10 MV, 18 MV, and 25 MV x-ray beams from Orion (4 MV), Saturne III (10 MV and 18 MV), and Sagittaire (25 MV) units. Dosimeters have been irradiated at 2 Gy in a polystyrene phantom, and in the following conditions: 15×15 cm^2 field, 5 or 10 cm depth depending on the beam quality, the measurement point being situated at the isocentre. An ionization chamber has been irradiated simultaneously, opposite to the TL dosimeter, to monitor the delivered dose.

The readings of the TL response were compared to the readings corresponding to the reference dosimeters.

The reading per gray decreases with increasing energy. If the reading of the dosimeters is presented as a function of the beam quality (QI), and normalized to the response for the ^{60}Co beam, the distribution of the data can be fitted by a straight line passing through $y = 1.000$ for the ^{60}Co beam and $y = 0.963$ (corresponding to a maximum variation of 3.7%) for the 25 MV x-ray beam (QI = 0.783), for both the readers.

5. Discussion

5.1. TL material

Lithium borate has been proposed as an alternative to lithium fluoride. With an effective atomic number of 7.4, $Li_2B_4O_7$ is more tissue equivalent than LiF, and little correction for beam energy has to be applied. Lithium borate doped with copper, $Li_2B_4O_7$:Cu, exhibits the additional advantage of presenting an important optical self-absorption. On the PCL3 reader, when choosing suitable reading temperatures, the response varies very slowly with the mass of powder contained in the cupel (a 10% variation of the mass leads to about 2%

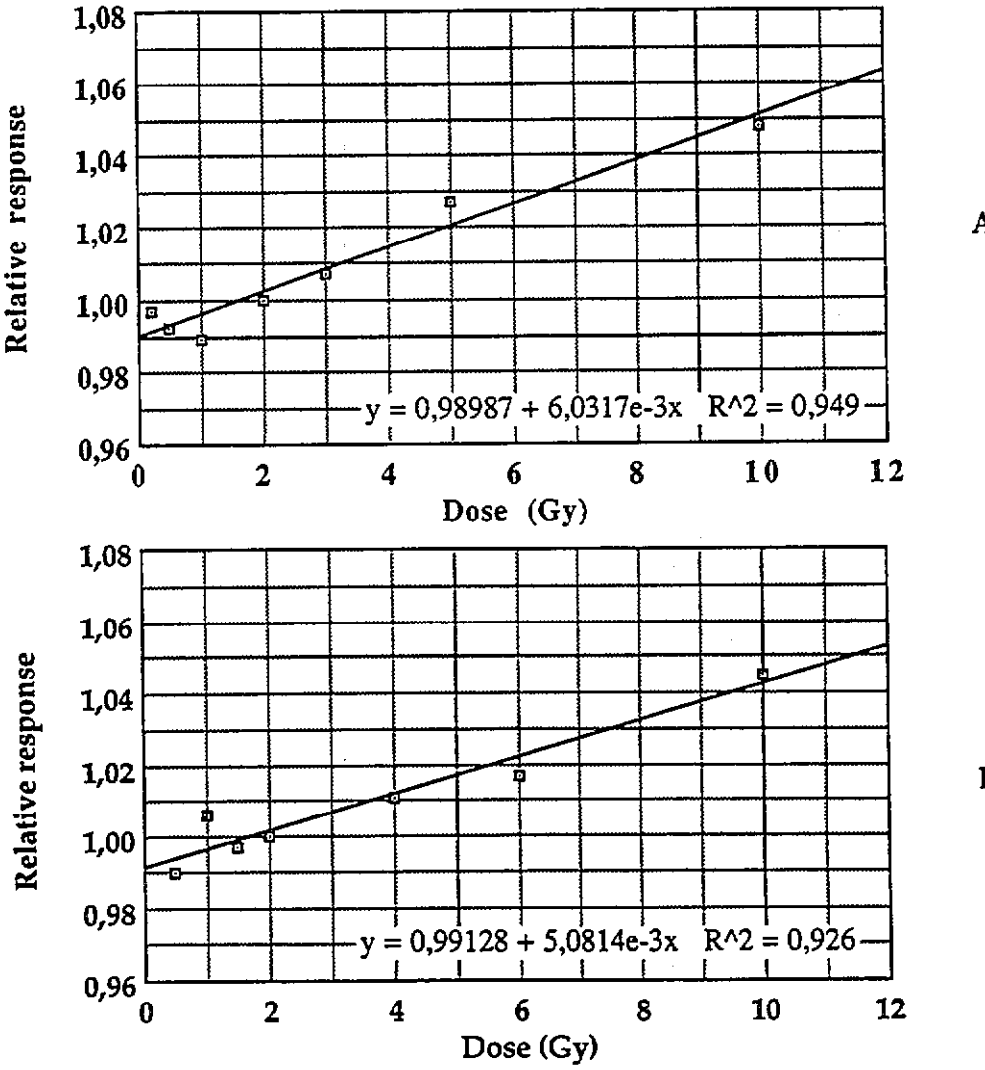

Figure 6. The variation of the TL measuring system relative sensitivity as a function of the absorbed dose (A) with the Saphymo manual reader and (B) with the Fimel PCL3 automatic reader. The responses are normalized to the response for 2 Gy.

variation in the response), provided the mass is adapted to the cupel diameter (Marinello *et al* 1990). So, the problem of a precise filling of the cupels is less critical, allowing time saving for this phase of the measurement procedure.

In spite of such advantages, $Li_2B_4O_7$:Cu presents other characteristics that make it questionable for our purpose. First, the boron contained in the crystal undergoes nuclear capture reactions with thermal neutrons ($^{10}B + n \rightarrow {}^4He(\alpha) + {}^7Li$) in high-energy photon beams. Therefore, it is not advisable for the dosimetry of photon beams with energies above 10 MeV.

Moreover, $Li_2B_4O_7$ exhibits an important thermal DRA, often quoted as greater than 10% for two months at room temperature (McKeever 1985), and cannot then be used properly for postal dosimetry.

Solid dosimeters have also been proposed instead of powder, because they are easier to handle, and they do not need to be weighed for the reading, but, as mentioned above, the dosimeters must be calibrated individually and regularly to reach a precision comparable with the one obtained with the powder. The choice of solid or powder dosimeters depends on the required precision and on the workload. In our experience, for this International Quality Assurance Network, the use of LiF powder is preferable.

5.2. Choice of the reader

There is no doubt that an automatic reader fits better with a widespread dosimetry programme such as the EC QA Network, provided that the reproducibility of the readings matches the requirements as do selected manual readers. We have shown that, on the PCL3, with five readings per dosimeter, the standard deviation of the mean ($1s$) can reach about 0.7%, i.e. the same standard deviation as obtained with three readings on the Saphymo manual reader. Moreover, it appears that, with the automatic reader, the repeatability of the readings depends critically on the heat transfer between the cupels and the ovens, and on the reflectivity of the cupels: the better the heat transfer and the lower the reflectivity, the better the repeatability. Recent measurements with cupels that benefited from a more highly polished undersurface and from a heat treatment darkening their surface (3 min at 500 °C) revealed noticeable improvements in the repeatability of the readings ($1s$ as good as 0.4% for the mean of three readings, without weighing the powder).

In the frame of the EC QA controls, the last 19 photon beams have been checked with a double series of dosimeters, allowing the readings to be performed both on the Saphymo and the PCL3 readers. The distributions of the results (i.e. of the ratios D_m/D_s) obtained on both instruments lead to means of 1.002 and 1.009, with respective standard deviations ($1s$) of 2.3% and 1.9%, for the Saphymo and the PCL3, respectively. The agreement between the two methods appears to be very good.

The present saving of human time with the automatic reader is in the order of a factor of two as far as the reading step of the measurement chain is concerned. The cupels are manually filled, but the development of an automatic device is under investigation. When it is available, the 'gain factor' is expected to be of the order of four.

5.3. Dose calculation and correction factors

(i) During the first two years of the EC Network (1992–1993), no correction was applied for photon beam attenuation in the LiF dosimeter's Perspex support although the dosimeters were calibrated in a homogeneous phantom. Measurements performed at the IAEA (Nyström *et al* 1993), and more recently at the IGR, have shown that the dose at the point of measurement of the TL dosimeters is decreased by about 1.5% for a ^{60}Co beam and 1% for a 4 MV x-ray beam, at 5 cm depth, by the attenuation in the Perspex holder. For higher energies, the correction remains smaller than 0.5%, at 5 cm or 10 cm depth depending on the beam quality.

Regarding the measurement of the beam quality index, the effect on the ratio D_{20}/D_{10} of the differential attenuation at 10 cm and 20 cm depths has been measured by the IAEA and estimated to be about 0.8% for a 4 MV x-ray beam, and less than 0.5% (0.2%) for a 20 MV x-ray beam (Nyström *et al* 1993).

(ii) The energy dependence of the dosimeter response has been measured several times at the IGR between 1990 and 1993. A linear variation of the response with the QI of the beam, with a maximum variation of 2.2–2.5% for the 25 MV x-ray beam (QI = 0.783) was first observed. A new series of measurements was performed and showed a large dispersion

of the values (1s of about 1.3% for each energy) and a greater variation of the response as a function of the radiation energy. A linear regression curve fitting all the measurements gives a maximum deviation of 3.7% for the 25 MV x-ray beam.

Measurements performed by the IAEA with TLD 700 Harshaw powder contained in the same polyethylene capsules also led to a linear decrease of the response with increasing beam quality index, but with a maximum decrease of 2.5% for a 20.9 MV x-ray beam (QI = 0.784) (Nyström *et al* 1993).

(iii) Regarding the DRA with time, a specific investigation has been performed and published by Delgado *et al* (1991, 1992). They used Harshaw TLD-100 chips in the radioprotection dose range (about 1 mGy). They showed that the observed instability of the response is not due to the lack of stability of trapped charges (Randall–Wilkins fading), but to changes in the trapped structure that occur during the storage before and after the irradiation of the dosimeters. This trap structure alteration is more intense before than after the irradiation (empty traps are less stable than filled traps), depends on the time of storage, increases with increasing temperature, and leads to an increase or a decrease of the response.

Our estimation of the DRA of the mailed dosimeters takes into account the fact that the alteration can be positive or negative, and that it can occur before or after the irradiation. The limit of our method is that we have to extrapolate the measurements from the monitoring dosimeters B, C, and D to what actually occurred to the mailed dosimeters, making the hypothesis that the DRA is always a linear function of the time, and that the slope of the variation is equal before and after the irradiation.

6. Conclusion

The pilot study has proven the suitability of the equipment and of the methodology used at the MC, taking into consideration the requirements of the European network with respect to the accuracy that should be reached with such a mailing procedure and a large number of measurements.

The global uncertainty linked to the general procedure is estimated to be better than 2% for both the beam output and the beam quality checks. Nevertheless, a number of possible small systematic errors dealing with the attenuation in the IAEA Perspex support and the energy dependence of the dosimeters should be kept under evaluation and corrected for.

During the mailed checks of the beam output performed on a total of 162 beams, 15 deviations greater than 6% have been detected. The probability of these deviations being due to uncertainties in the methodology is very low.

The method has been extended to other kinds of check, such as the check of the dose distribution in photon beams with a multipurpose phantom (Bridier *et al* 1993).

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