A QUALITY AUDIT PROGRAM FOR EXTERNAL BEAM RADIOTHERAPY

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Abstract - For more than 25 years, the University of Texas M. D. Anderson Cancer Center has had a quality audit program using mailed dosimeters to verify radiation therapy machine output. Two programs, one compulsory and one voluntary, presently monitor therapy beams at more than 1000 megavoltage-therapy facilities. A successful program requires two major components: a high-precision thermoluminescent dosimeter (TLD) system and dedicated staff that interact closely with the users to resolve discrepancies. The TLD system, the logistics used, and the human interaction of these programs are described. Examples show that the programs can identify major discrepancies, exceeding 5%, as well as discrepancies as small as 3%.

INTRODUCTION

The University of Texas M.D. Anderson Cancer Center has two highly successful, mailed quality audit programs for external beam radiation therapy using TLDs. Together, the programs annually monitor approximately 10,000 beams at more than 1000 institutions throughout the United States, Canada, and a few other countries. Originally, the programs were designed to yield a check of beam calibration for photons only. The programs were expanded in the early 1980s to include calibration checks and spot checks of radiation energy for electron therapy beams. The first program, now called Radiation Dosimetry Services (RDS), is a voluntary for-fee service with TLDs mailed at the frequency specified by the institution, typically monthly, quarterly, semiannually, or annually. The second program is through the Radiological Physics Center (RPC), a National Cancer Institute (NCI) grant-supported program. This program is compulsory for all megavoltage facilities that participate in NCI-funded cooperative clinical trials involving radiation therapy. Since one program is voluntary and the other compulsory, the experiences of each differ.

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ANECDOTAL CASES

Table 1 presents a series of typical cases where the TLD program identified a dosimetry problem; the institution corrected the problem and the TLD results improved. The programs originally were designed to identify major dosimetry problems, i.e., discrepancies exceeding 5%. Cases 1 through 4 illustrate that the programs have been effective in identifying these problems. Furthermore, cases 5 and 6 show that the TLD programs have also flagged discrepancies of 3% or less, which motivated the local physicist to identify minor dosimetry problems. Cases 5 and 6 are from the voluntary program, where the physicist welcomed an opportunity to resolve the problem. Data in Figure 1 are for a participant in the compulsory program; this is an unusual situation, presently under investigation. The TLD/INST ratio has varied from 0.96 to 1.08. Twice during the last several years, the results were outside our criteria; however, repeat TLD results were within the criteria. This situation was ultimately flagged when the physicist returned the TLDs unirradiated along with a nasty note. After investigation, the RPC physicist discovered that the institution's physicist calibrated his beam either at d-max or at depth (5 cm) in polystyrene. Whenever he calibrated at d-max, the TLD results were within 2%; when he calibrated at depth, the results varied considerably and changed dramatically following the RPC dosimetry review visit in 1989. Following several phone calls, the physicist at the institution is now willing to help us resolve the discrepancy.

In order for the quality audit program to distinguish minor problems, the TLD system must have high accuracy and high precision. In addition, a program must have a high sensitivity provided by the management of the program. Therefore, in addition to the high-quality technical system, human interaction gives our programs a sensitivity that we believe is unparalleled. This presentation will describe briefly the physical aspects of the TLD system and then discuss the most significant component, the human element.

DOSIMETERS

We have chosen lithium fluoride (LiF) TLDs in throw-away powder form. A large crystal (approximately 4 kg) of LiF doped with magnesium and titanium (TLD 100) is grown by Harshaw/Bicron, crushed, annealed, and homogenized before shipment to the Radiation Detection Company. The Radiation Detection Company dispenses the powder into capsules containing approximately 30 mg of powder each.

In the past, approximately 100,000 capsules have been made from a single LiF crystal. The most recent crystal is larger and the amount in each capsule is smaller, so we anticipate having 200,000 capsules from the present batch. There are two major reasons that we use powder: better precision and simpler bookkeeping. With the high level of quality control at Harshaw and the Radiation Detection Company, we are assured of a precision of $\pm 1\%$ (1 standard deviation for a single capsule irradiated with a known quantity of cobalt-60) for the entire batch of 100,000 to 200,000 samples without a sophisticated bookkeeping system.

IRRADIATION PHANTOMS

The choice of irradiation phantom is not as simple as the choice of dosimeter. Table 2 lists the criteria for a phantom for a mailable quality audit program. Three types of phantoms have been used for mailed TLD systems. The International Atomic Energy Agency (IAEA) has chosen a water phantom and mails only a small TLD holder to be set in a pail of water (Svensson et al. 1990). Each participant provides the pail; therefore, cost to the IAEA is minimal for constructing the phantom and shipping the TLD holder. From 1974 to 1986, most of the Centers for Radiological Physics (CRPs) used plastic full-scatter phantoms with the TLD located at depth in the plastic (Samulski et al. 1981). This phantom is expensive to build and to mail; however, it is probably the best for reproducibility of set-up. For the RPC and RDS system, we have chosen a compromise; these phantoms are discussed by Kirby et al. (1986). For photons an acrylic miniphantom block contains TLDs located in the center of the block with full build-up thickness on all sides. The block is placed on a "scatter free" platform as shown in Figure 2. For electrons the phantom is an acrylic cube approximately 9 cm on a side. TLDs are placed near d-max to check output and in the fall-off region to verify radiation energy, as illustrated in Figure 3. Our system allows precise positioning of the TLD and easy set-up by the user. For redundancy, three dosimeters are placed at each depth of measurement and a "reading" is the average of the three dosimeters.

READER SYSTEM

Our experience is that the simplest reader system is the best, and we presently use the Teledyne Model 7300 reader. To improve precision. we dispense approximately 20 mg of powder and mass the powder using a Mettler microbalance. The reader and balance are interfaced to a computer; the glow curve is displayed on the computer screen and integrated using our own software. Bar coding helps manage the paper work associated with receipt of dosimeters, reading of the samples, and progress of reports.

COMMISSIONING

At the present time, a single batch of TLD powder lasts 18 to 30 months. Table 3 lists the steps required to commission a batch prior to use. In chronological order, we first verify that the batch has acceptable uniformity of response. At least 100 capsules are chosen randomly from various packets of dosimeters, irradiated to the same cobalt-60 dose, and read in several reading sessions. One standard deviation of 1% or better is considered acceptable. We then check the linearity of response over the range of dose from 100 to 500 cGy. Typically we find supralinearity of response, with approximately an 8% change in relative sensitivity, from which a linearity correction is derived. Fading of response with time is also a consideration. We apply a two-step correction factor, assuming that the TLDs fade 0.1% per day for the first 50 days and do not fade thereafter. Data confirming the applicability of this assumption are shown in Figure 4 for Batch B/90. We are presently considering a non-linear fit to the fading data. To minimize the magnitude of the corrections, we ask institutions to irradiate near 3 Gy and we use standards irradiated within a few days of the irradiation of the mailed TLD.

The most difficult characteristic to determine is the energy dependence. This correction accounts not only for the energy response of the TLD but also for the different scattering conditions of the various blocks. Figure 5 shows data for TLD Batch 6/88 for photons from cobalt-60 to 25-MV x-rays. We use block-specific corrections, so the correction factors take on a step function shape as shown. Similar data are collected for electrons. The energy correction factors are based on measurements at depth in a water phantom, using a cylindrical ion chamber and calculations recommended by the AAPM Task Group 21 calibration protocol (AAPM 1983), normalized to unity at cobalt-60 energy.

Characteristics of a new batch of TLDs are similar to previous batches. Comparison across batches provides additional assurance that commissioning procedures are correct and shows the value of having long experience with the same type of TLD.

PRECISION

Our TLD system is based on calibration with a cobalt-60 beam. All calculations are based on the AAPM TG-21 calibration protocol (AAPM 1983), using ion chambers with calibrations directly traceable to National Institute of Standards and Technology. We therefore consider the accuracy of the system to be in compliance with national standards. Thus, we will consider here only the precision, or reproducibility, of the TLD system. In a recent publication, Kirby et al. (1992) discuss the theoretical precision of the TLD system in detail. As suggested earlier, 1 standard deviation of a single reading is typically $\pm 1\%$. Theory predicts that combining errors for linearity, fading, and energy dependence yields a variance of approximately 3% for a single dosimeter, which results in an uncertainty of 5% at a confidence level in excess of 90% for a single data point (three dosimeters).

The above theoretical assessment of precision is verified by our experience. Since 1984, approximately 4% of all photon checks and 7% of all electron checks are outside our $\pm 5\%$ criteria. Some of these checks (1%-2%) represent real discrepancies in calibration or set-up, with the remainder apparently due to statistical variations. In addition, ion chamber measurements by the RPC at the participating institutions have a standard deviation of the ratio RPC/INST of 1.8% for photons and 2.2% for electrons. The standard deviation of the TLD/INST over the same period of time is 2.7% for photons and 3.0% for electrons. This 1% increase in uncertainty is also consistent with the theoretical estimate of precision.

The effort required to maintain the precision of the TLD system is illustrated by the fact that approximately one-third of our TLD are used in quality control of the system.

LOGISTICS

Communication with users is paramount to the success of a mailed quality audit program and it is the human factor that makes our programs effective. Our for-fee program (RDS) requires that primary communication be with a physicist rather than a machine technician, therapist, or radiation oncologist. This assures that the physicist is in charge of irradiation of dosimeters, receives the reports, and resolves discrepancies.

The instructions and forms to be completed by the user must be short, simple, and concise. The RDS program limits the instruction to one page each for electrons and photons, while the RPC combines instructions for both photons and electrons into a two-page instruction sheet. We have found a diagram to be particularly helpful, such as seen in Figures 2 and 3.

We recommend the following for irradiation of the dosimeters:

- TLD set-up should closely simulate patient set-up.
- Irradiation time should be similar to times used clinically. (We use 300 cGy.)

- TLDs should be irradiated by the physicist in collaboration with the therapist and/or radiation oncologist who normally treat the patient. It is particularly important for a consultant physicist to ensure that the oncologist and therapist are using the calibration information in a manner consistent with the measurements.

- TLDs should be irradiated using the output used clinically. (This is a corollary to the preceding comment.)

The data sheet completed by the user also should be short and concise. Information should include:

- Institution, therapy-beam identification, and name of the person irradiating the TLDs, including his telephone number.

- Identification of the phantom blocks.

- TLD irradiation condition: field size, distance to platform, monitor (time) setting.

- Dose to the reference point. It should be clear that this does not relate to the dose given to the TLDs but rather to the absorbed dose at the institution's standard reference point (e.g., dose at d-max for standard SSD). One or two redundant questions are helpful to identify potential misunderstandings.

- Information concerning the calibration protocol used.

The report issued to the physicist includes the following:

- Date of irradiation.

- Identification of institution, therapy unit/beam, and person irradiating the TLDs.

- Distance to the reference point.

- Institution's stated dose and dose measured by TLD.

- Ratio of absorbed dose determined by TLD and that stated by the institution, expressed as TLD/INST.

- Date TLD read.

- Signature of the reviewing physicist.

The report also includes the following qualifying statements which state the intent of the program, the precision of the program, and the criterion for a satisfactory check.

> THIS INFORMATION SHOULD BE USED ONLY AS A CHECK OF MACHINE OPERATION AND NOT AS A MACHINE CALIBRATION, nor as an alternative to frequent calibrations by a qualified physicist.

The variance of the dose determined by a single TLD is less than 3%. The average of readings for three dosimeters, therefore, has an uncertainty of 5% at a confidence level in excess of 90%. This analysis does not include uncertainties in the institution's irradiation technique. A typical therapy unit may have increased uncertainty.

Agreement within 5% is considered a satisfactory check.

RESOLUTION OF DISCREPANCIES

The TLD results are processed by a computer and a calculation sheet is generated, as well as the report to the user. Each calculation sheet and report is reviewed by a dosimetrist and/or a physicist. The review verifies that the TLD was set properly and that we interpreted the institution's data correctly in our calculations. The TLD history for the therapy unit is also printed on our calculation sheet so that our reviewer can look for changes in the results or identify trends.

Interaction with the institution's physicist is necessary to resolve discrepancies. If the TLD results disagree with the institution's stated dose by more than 5%, we contact the institution by phone immediately. We also contact the institution by telephone if there appears to be a trend developing or if there are questions regarding irradiation set-up or the institution's data. During the telephone conversation, we discuss the set-up, the possibility of extraneous radiation to the TLD, whether the physicist measured the machine output prior to irradiation of the TLD, the details of his calibration procedures (phantom, distance, chamber, etc.), and the actual numbers used in the calculation of dose. Frequently, the origin of the discrepancy is discovered in this telephone conversation. Regardless of whether we believe the discrepancy has been resolved, a repeat TLD is sent to verify the findings of the telephone conversation. Frequently, we provide the repeat TLD free of charge to the institution.

It is this follow-up phase that is the principal difference between the RDS (voluntary) program and the RPC (compulsory) program. Those institutions who subscribe to the program on a voluntary basis tend to be more willing to search for the problem during the telephone conversation. If the RDS dosimetrists cannot resolve the discrepancy, the problem is turned over to an experienced physicist for further investigation. In a very few cases, intractable discrepancies have been resolved by one of our physicists visiting the institution, with an ion chamber and water phantom in order to verify the machine calibration.

The RPC (compulsory) program finds it more often must perform on-site reviews of institutions to resolve discrepancies. Five to eight institutions are visited per year as a result of unresolved TLD discrepancies. Approximately 50% of the time, the ion chamber verifies the TLD results. The remainder of the time, the ion chamber measurements have no apparent relation to the TLD results. However, of 93 institutions visited for an intractable TLD problem, only one institution has had a repeat of the TLD discrepancy. This suggests that the institutions have changed their TLD irradiation or dose calibration procedures without informing us.

We believe strongly that it is this follow-up procedure that gives our quality audit programs their good track record.

CONCLUSIONS

The University of Texas M. D. Anderson Cancer Center in Houston, Texas, has two quality audit programs to verify calibration of photon and electron radiotherapy beams using mailed TLDs. These two programs presently monitor therapy units at more than 1000 megavoltage-therapy facilities in the U.S., Canada, and a few facilities elsewhere in the world. These programs require a high-precision mailed TLD system using powdered LiF in acrylic phantoms. The variance of a single dosimeter is less than 3%, and a single data point (three TLDs) has a precision of ±5% at a greater than 90% confidence level.

In addition to the high precision of the physical system, an extensive follow-up program by telephone to resolve discrepancies is in place. Examples show that the program can detect major discrepancies (> ±5%); it may also suggest discrepancies as low as 3%. Collaboration with the local physicist helps him to find and resolve discrepancies.

Our programs are unique, both in volume and longevity. The large volume helps to maintain the precision and to keep cost at a reasonable level. A long history obviously gives the benefit of experience, but also allows us to compare present results with previous data. We are always alert to ways to improve our programs; however, the impact and appropriateness of even minor changes are carefully considered before they are implemented.

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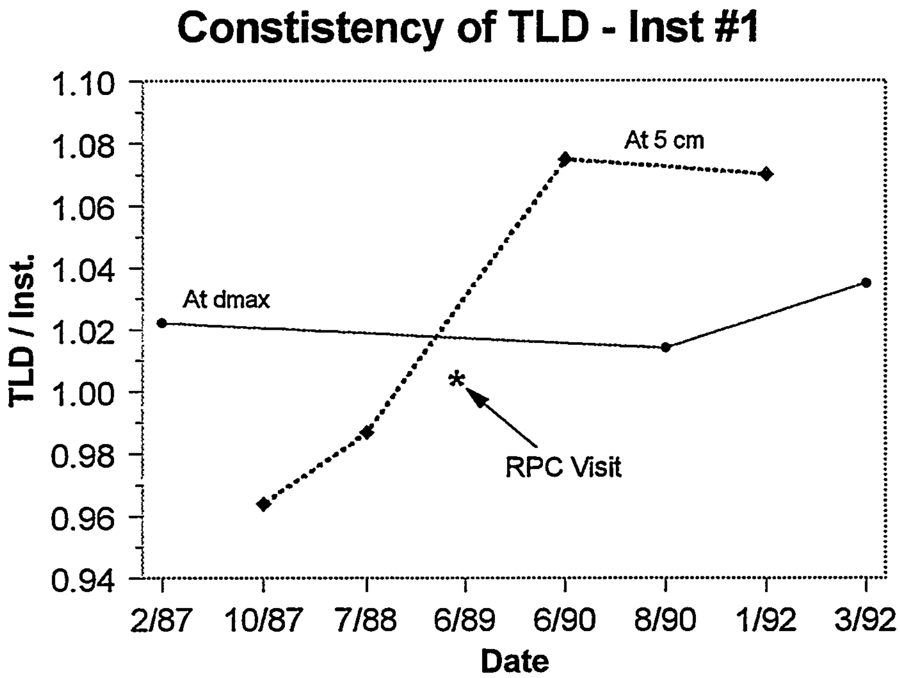

Figure 1 - Results of six mailed TLDs over a 5-year period on a 6-MV x-ray beam. The results of ion chamber measurements by the RPC on this beam in 1989 are also included. The results appeared to have wide variations until the trend was identified. The institution calibrated the beam either by measurements at d-max or a 5-cm depth in a polystyrene phantom. The disparity between the two is presently under investigation.

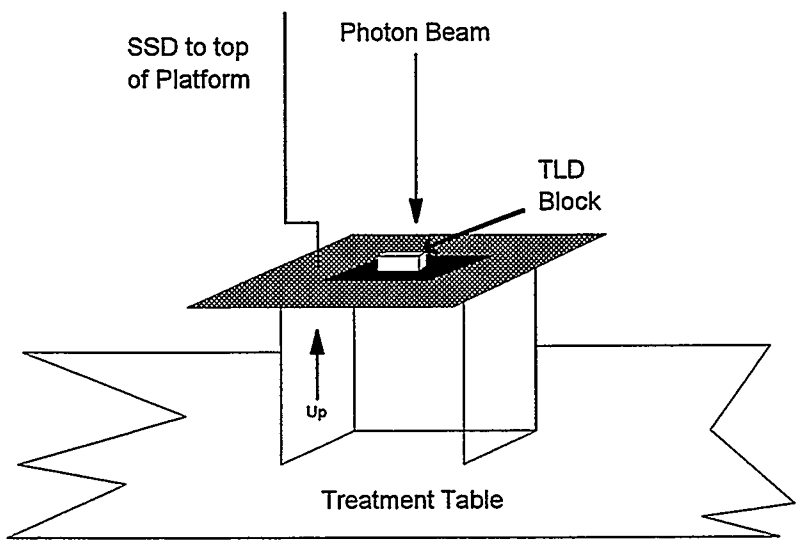

Figure 2 - Schematic diagram of the photon irradiation geometry for the TLDs. The TLD block is energy dependent and just large enough to assure full build-up in all directions. The platform is of 1/8" acrylic and therefore nearly scatter-free.

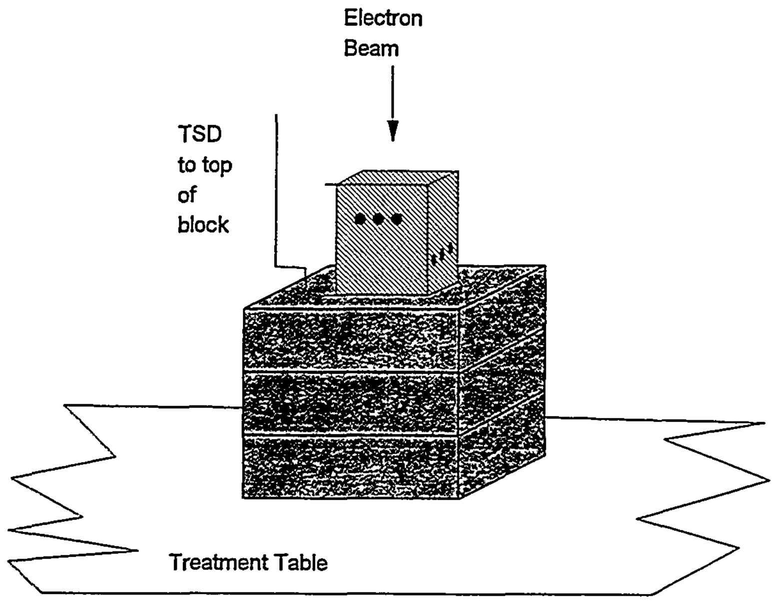

Figure 3 - Schematic Diagram of the electron irradiation geometry. The block holding the TLDs is shown partially withdraw to demonstrate the location of the two sets of TLDs, one near d-max and one in the fall-off region.

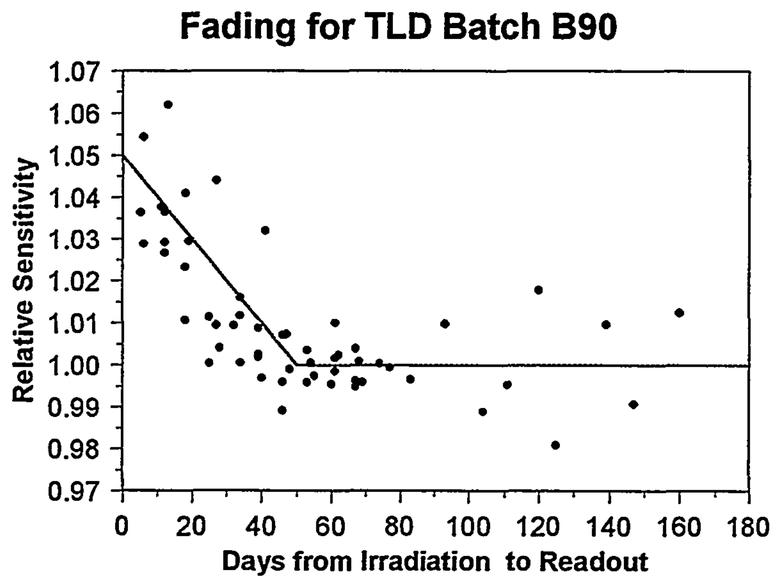

Figure 4 - Fading characteristics of the TLDs. Data points are represented, as well as the theoretical curve (solid line). Our TLDs fade approximately 0.1% per day for the first 50 days.

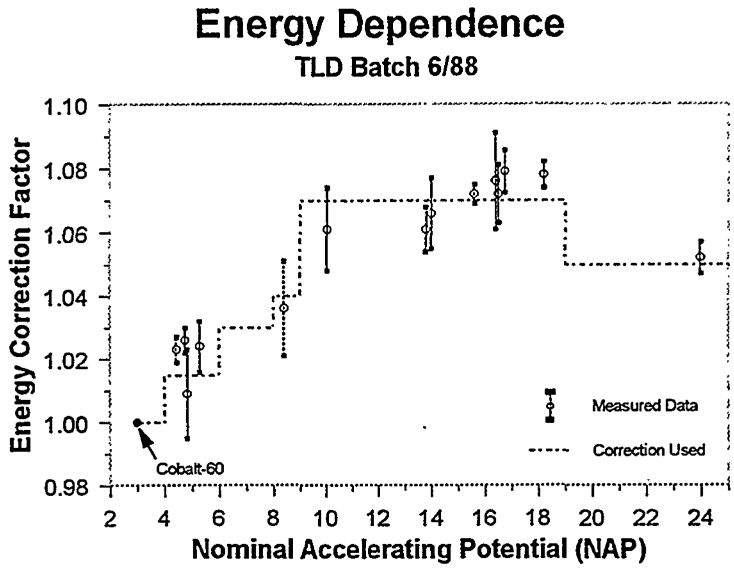

Figure 5 - Dependence of the TLD system on the photon energy. Various irradiation blocks are used over a range of energies. The correction factor used is specific to the block and is indicated by the dashed line.

Table 1 - Typical Discrepancies Identified by the Mailed TLD Programs and Subsequently Resolved by the Institution.

Case No.	Initial TLD/Inst	Problem Corrected	Final TLD/Inst
1	1.17	Physicist trained chief tech to do daily output checks on 20-MV x-ray beam. Tech set up 100-cm SSD, not 100-cm SAD. Calibration depth = 7 cm.	~1.00
2	1.06	On first check, physicist was filling water tank to wrong mark on the water phantom.	1.00
3	0.90 on $7e^-$ 0.94 on $11e^-$	For electrons, institution calibrated with a horizontal beam; TLDs were irradiated with a vertical beam. Severe angular dependence of output was discovered.	
4	1.06 to 1.07	Institution's constancy check meter had failed to detect change in machine output.	1.01
5	1.03 to 1.04	After TLD/Inst. was near 1.00 for 2 years, it jumped to 1.03 and 1.04 for 2 TLDs. Physicist discovered his correction for solid water was multiplied, not divided.	1.00
6	1.03	After TLD/Inst. was near 1.00 for 2 years, it jumped to 1.03. Physicist "corrected a problem with the timer error."	~1.00

Table 2 - Criteria in the Choice of a Mailable Phantom.

Criteria	Preferred Phantom
Minimum cost	Water
Easily mailable	Water or plastic
Ease of use	Plastic
Reliable set-up	Plastic

Table 3 - Commissioning of a TLD Batch

Calibrate with cobalt-60 as "standard." Check response for: • Uniformity across batch • Linearity • Fading with time • Energy dependence