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Feasibility study of silica bead thermoluminescence detectors (TLDs) in an external radiotherapy dosimetry audit programme

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Abstract

Purpose

Investigating the feasibility of using low-cost commercially available silica beads as novel thermo-luminescence dosimeters (TLD) for postal dosimetry audit.

Methods

A mail-based dosimetry audit was designed to assess the positional and dosimetric accuracy of SABR-lung treatment delivery using alanine and EBT3-film, placed in a CIRS-anthropomorphic thorax phantom. In conjunction, the silica beads were dosimetrically characterized as TLDs and cross-calibrated against the alanine. A CT-scan of the phantom with pre-delineated volumes was sent to 20 RT centres and used to create a SABR plan using local current protocols and techniques. The silica beads were held in an insert, designed to match that of the alanine holder and ionisation chamber to give the same measurement length. The doses determined by the silica beads were compared to those measured by alanine, the local ionisation chamber, film and the TPS calculation.

Results

The mean percentage difference between the doses measured by the silica beads and the calculated doses by the TPS was found to be 0.7% and differed by 0.6%, 0.7 %, and 1.3 % from the alanine, film and local ionisation chamber measurements respectively.

Conclusions

Results obtained with the silica beads agree well with those obtained from conventional detectors including alanine, film and ionisation chambers. This together with the waterproof and inert characteristics and minimal dose fading associated with silica bead TLDs confirm their potential as a postal dosimetry audit tool in both water and plastic phantoms which could withstand challenges of temperature and humidity variation, as well as postal service delays.

Keywords: Dosimetry audit, radiotherapy, SABR, Thermoluminescent detectors

1. Introduction

Radiotherapy audit provides an external independent assessment of the dosimetry and can help to identify possible improvements and also find issues which may need addressing immediately [1, 2, 3, 4, 5, 6].

Although the use of thermoluminescence dosimeters (TLD) as the standard tool for postal dose audits is common practice [7, 8, 3, 9] TLDs require improvements to face the new challenges introduced by advanced radiotherapy techniques, and recently several other types of detector have been used for audit including *seven29 array* (PTW-Freiburg GmbH, Germany) and *InLight® nanoDot OSLD system* [4, 5, 10]. Advanced radiotherapy techniques very often use small radiation fields with high dose gradients [11, 12] which introduce further challenges in dosimetry. The common and well-established small TLDs, such as 1 mm^3 LiF: Mg, Ti have been designed for traditional radiotherapy practice with an upper dose range limit of approximately 10 Gy and therefore are not suitable for dose evaluation of high dose advanced techniques such as SABR. Furthermore, for postal dosimetry audit of such techniques, especially when complex dose distributions and field arrangements are used, the best detector would be a micro detector with a linear response to a large dynamic dose range and ideally be a detector that also has a very low fading, non-hygroscopic nature and is robust, as irradiation and postage return may take some time [12, 13].

Silica beads have previously been characterised as novel high spatial resolution micro TLDs [14, 15, 16, 17, 18]. The particular silica beads employed have several potentially favourable physical characteristics as dosimeters in postal dosimetry audit of advanced radiotherapy. They are small in size (2 mm diameter and 1 mm thickness), chemically inert, inexpensive, readily available, and reusable. They exhibit minimal fading compared with LiF: Mg, Ti TLDs, have a high sensitivity and a large dynamic dose range that remains linear ($R^2 \geq 0.999$) from 1 cGy to 50 Gy (i. e. the investigated dose range). The dose response has been found to be independent of dose rate and incidence of beam angle which makes it suitable for delivery techniques such as VMAT and non-coplanar beams. Although silica beads are silicon based TLDs and not soft-tissue equivalent, they have shown a close to uniform response over the MV photon energy range which is commonly used in advanced radiotherapy techniques. These properties suggest their practical use as TL dosimeters for radiotherapy dosimetry.

In this work the feasibility of using silica bead TLDs for the lung radiotherapy postal dosimetry audit is assessed in conjunction with the UK SABR Lung Consortium dose audit run by the Consortium QA group. Silica beads were placed in the CIRS phantom where heterogeneity is present and the performance of the silica beads in a non-equilibrium condition (near the tissue/lung interfaces) was evaluated.

Stereotactic ablative body radiotherapy (SABR) is an advanced radiotherapy technique that uses low fractionation, high dose treatments, stereotactically directed to the tumour. For example, in SABR for lung a prescription dose of 18 Gy/fraction (in 3 fractions) to the 80% isodose is typically prescribed [19]. In such a situation where a high dose is delivered in a few fractions, there are fewer opportunities to correct or adapt the treatment dose. An error in any single

fraction would have a larger proportional impact and therefore, the dosimetric accuracy is expected to have a greater effect on radiotherapy outcome. It is therefore essential that such treatments be verified by undertaking appropriate quality assurance (QA). Dose errors in such cases of the order of 5% can result in 10 to 20% changes in tumour control probability and up to 20 to 30% changes in normal tissue complication probabilities [20].

The audit was designed to assess the positional and dosimetric accuracy of SABR lung treatment delivery across UK. This was achieved with the use of alanine pellets and EBT3 GafChromic film dosimetry, placed in a CIRS lung phantom [21, 22]. 20 volunteer centres within the UK collaborated with this feasibility study.

2. Material and methods

2.1 Silica beads

A batch of transparent silica beads, 2 mm diameter and 1 mm thick outer shell (*Petite*: Stock#: G42010, Mill Hill, Japan) with material composition (by weight): C-8.93%, O-42.18%, Na-10.55%, Al-1.3%, Si-33.62%, K-1.09%, Ca-1.92%, Fe-0.37% [15] was selected for this work. The silica beads were initially produced as jewellery silica beads and preparation was required for them to be used as TLDs. The silica beads were acid washed in an ultrasonic bath in order to remove the surface-applied colouration and were screened for variation in mass using an Ohaus Adventurer Analytical balance. Overall, 280 silica beads of mass 3.4 ± 0.1 mg were used. For each measurement, 20 silica beads were threaded along a cotton yarn, in order to have the same effective length of measurement as a NE2571 graphite-walled cylindrical ionisation chamber (23 mm). In this arrangement, a high resolution dose profile measurement was obtained as well as the mean value of all 20 silica beads were comparable to the dose measured by each centre's local ionisation chambers. They were then loaded into a custom-built insert.

2.2 Silica bead readout

A Harshaw 4500 planchet TLD reader was employed to readout the silica beads at 300 °C at a ramp-rate of 35 °C/s following a preheat treatment of 140 °C for 10 s. To consider the post radiation time delay for a potential postal service, readings were only obtained following a post-irradiation delay of 10 days. Between each use, the beads were subsequently annealed for 1 h at 400 °C and then kept 24 h at room temperature under dark conditions to ensure they were stabilised prior to the next irradiation. A detailed description of the preparation and annealing procedure has previously been published [14].

2.3 Silica beads holder insert

Given the phantom was designed for film and ionisation chamber dosimetry, custom made inserts matching the external shape of the NE2571 type ionisation chamber were made from tissue equivalent material (PEEK) in order to hold the silica bead TLDs and the alanine in an identical measurement position. All the inserts were coded to keep track of individual silica beads. Three inserts and a stem were packed in a black card box (figure 1) and posted to each centre at the same time as the CIRS phantom, alanine and film were sent by the SABR consortium audit team.

2.4 CIRS Lung phantom

Five CIRS IMRT Thorax Phantoms (The CIRS Model 002LFC) (figure 1) were used for the Lung SABR dose audit. This is an anthropomorphic phantom with lungs and a spinal cord in a thorax shaped solid water, which can be used for commissioning as well as comparison of TPS calculated plans and measurements.

A CT scan of a CIRS lung phantom was performed by the SABR consortium audit team prior to the national audit with 1.25 mm slice spacing and thickness. Volumes relating to the internal target volume (ITV) and the position of the alanine pellets were pre-delineated. This CT scan set was sent to all centres and was loaded into their respective treatment planning system. The CT calibration curves were sufficiently similar to justify this single scan and uncertainty was estimated to be no larger than 0.5% [23].

Figure 1: (a), The CIRS Lung phantom with silica bead insert shown by a red circle. (b), the silica bead holder, in which silica beads are loaded. (c). schematic view of silica bead insert, and (d), 20 silica bead TLDs arranged on a piece of cotton yarn.

2.5 Audit Documents

In addition to dosimeters, the following documents, dosimetry protocols and instruction sheets were prepared and sent to each centre:

- A dosimetry audit protocol, which was prepared by the SABR consortium audit team, provided explanation of the phantom description, handling, CT-scanning and planning, EBT3 GafChromic film dosimetry and procedures for returning film for processing, as well as return of the alanine dosimeters to the National Physical Laboratory for readout.

- A GafChromic film irradiation record form
- An alanine irradiation record form
- Silica beads introductory document
- Silica beads dosimetry instructions and irradiation record form

2.6 Measurement procedure

2.6.1 Silica beads calibration

This batch of silica beads has been dosimetrically characterised in the previous studies and the details of characterisation measurements are published in earlier publications [14 and 15]. Linearity of dose response covering the range of radiotherapy dose levels (1cGy to 50Gy), had a correlation coefficient of $R^2 \geq 0.999$; therefore, the large dose differences between reference dose measurement and the audit dose levels can be considered to have a negligible calibration error. Energy response was fairly uniform across the MV photon beams and the maximum percentage difference compared to that obtained at 6 MV photons being -3.8% for 15 MV photons [15]. The energy response is considered of relevance for the use of dosimeters in postal audit situations where each institution may have slightly different quality index (QI) for their respective photon energies thus ensuring that the calibration may still be considered valid when same nominal beam energy is used.

The silica beads had a batch homogeneity of 8% (SD = 1) and so individual calibration factors were determined. This relative calibration was performed in a 6 MV clinical photon beam (TPR_{20/10} = 0.670) with a field size of $10 \times 10 \text{ cm}^2$. The calibration dose was 10 Gy at 5 cm depth in a Solid-Water® phantom. This beam quality was chosen as all radiotherapy centres employed 6 MV photon beams for their respective audit plans. A detailed description of the calibration procedure has been published previously [17].

2.6.2 Absolute dose measurements using alanine dosimeters

For absolute dosimetry, the silica beads were cross calibrated against alanine dosimeters in reference conditions. To perform absolute dosimetry with sufficient accuracy using alanine pellets, a dose of greater than 10 Gy is ideally required [24]. At 10 Gy, the uncertainty associated with the calibration of alanine dosimeters is 0.85% (SD = 1) and the pellet to pellet reproducibility is 0.5% (SD = 1) [24, 25]. Centres were therefore requested to irradiate a set of silica beads at a dose of 10 Gy at the same beam energy and under the same experimental conditions. The local ionisation chamber was also given 10Gy under these conditions.

The irradiated alanine pellets were analysed by the National Physical Laboratory using an EPR spectrometer and the results were reported in terms of dose (Gy).

2.6.3 SABR Plan

Each centre created a SABR plan on the scan of the CIRS lung phantom using their current planning protocol and technique. The plan covered the Planning Target Volume (PTV), which contained film, 9 alanine pellets and thus also the silica beads that in turn sit along the central

measurement axis of the alanine pellets. The position of the silica beads were close to the film, but not identical positioning (figure 2).

The setup of the SABR plan was first checked with the local ionisation chamber by placing the chamber in the posterior part of the left lung. An identical irradiation was then given to a set of silica beads. The phantom was next dismantled, the gafchromic film and alanine pellets were then put in position and the measurement was performed for the main audit.

The film analysis was performed by aligning the measured and calculated dose grids using the phantom pin coordinates (± 1 mm). The mean dose for the areas enclosed by the calculated 100% isodose line, in both the measured and calculated dose distributions were compared to alanine and silica bead dose measurements. The detailed procedure for film and alanine irradiation and analysis is given in a separate paper [22].

Figure 2: An example of the dose distribution of the treatment plan, which covered the PTV and contained 9 alanine pellets, film or a string of silica beads that sit along the central measurement axis of the alanine pellets (an overlapped picture of 20 silica beads threaded on a black cotton yarn and 9 alanine pellet outlines are shown to clarify the position of silica beads relative to the alanine pellets). The alanine pellets are positioned in the effective volume of an NE2571 ionisation chamber in turn.

2.6.4 Uncertainty analysis

Three major sources of uncertainty in the dose determination using the bead TLDs were identified:

- uncertainties associated with the calibration of the silica bead TLDs consistency against the alanine dosimeters
- uncertainties in the determination of individual sensitivity correction factors for the silica bead TLDs
- the uncertainty associated with the silica bead TLD themselves: linearity, fading during the readout process, and the TLD readout process

Dose response linearity, fading, and energy corrections factors are commonly applied for TLD analysis [26]. However, the fading and energy correction factors were negligible for this work as the absolute dose calibrations for the silica beads were performed on the day of read out and all treatment plans utilised 6 MV energy. Small variations of quality index for this nominal energy among facilities was considered to have a minimal effect. The uncertainty budgets for the silica bead TLDs quantified in table 1.

Table 1: The uncertainty budgets for the individual silica bead TLDs

Source of uncertainty	Relative standard uncertainty (%), SD = 2
Cross calibration of the TLD against alanine dosimeters	1.7
Determination of individual sensitivity correction factors for each TLD	1.7
Dose response linearity of silica beads	0.1
TLD reading process	2
Calculated standard uncertainty (quadratic summation)	3.13

With regard to the TLD readout process standard deviations of the silica bead TLDs are derived from the response of dosimeters to the same dose. The reproducibility of each individual TLD was found to depend on the stability of the TLD reader output as well as consistency in the positioning of beads on the planchet and annealing procedure [13, 14, and 15].

The overall uncertainty associated with alanine dosimetry during this audit ranged from 2.0 to 1.8% (10–24 Gy; SD = 2) and 2.6% for the film [22].

No phantom dependent correction has been applied. The geometry and density variations between five identical phantoms were checked and found to be negligible.

The analysis of percentage differences of silica beads results with alanine, ionisation chamber and TPS may be affected by small errors in the positioning of the TLD holders. For the majority of plans the dose distribution within the treatment volume is uniform and any movement of the TLD would change the dose by up to a maximum of 2.2% for a 5 mm shift from the position stated, which is the highest possible deviation of dose distribution across the 5 mm diameter alanine pellet.

3. Results

22 SABR treatment plans from 20 centres were measured. Delivery techniques varied amongst the centres; 6 centres used conformal radiotherapy, 11 centres used Volumetric Modulated Arc Therapy (VMAT) and 3 centres used CyberKnife. All centres employed 6 MV photon beams. The silica bead results were analysed after correction for the calibration against the alanine reference measurement. The percentage differences of SABR plan doses measured with silica beads from alanine, film, local ionisation chamber and TPS predicted doses are shown in figure 3. Figure 4 is showing an example of dose profile across the active volume of ionisation chamber obtained by silica beads and alanine pellets in comparison with the TPS.

Figure 3: A histogram of comparison between silica bead results and measurements with alanine, ionisation chamber, film and TPS expected doses.

Figure 4: Dose profile obtained by silica beads and alanine pellets in comparison with the TPS (Expanded uncertainty (SD=2) indicated).

4. Discussion

In this work, silica beads were used for a feasibility study of a dosimetry audit of SABR lung treatments performing point dose measurements in a CIRS phantom where heterogeneity is present and the performance of the silica beads in a non-equilibrium condition (near the tissue/lung interfaces) was evaluated.

Their performance was compared with alanine, ionisation chamber and film dosimeters. The mean percentage difference between the doses measured by the silica beads and the calculated doses by the TPS were found to be 0.7% (± 2.0) and differed by 0.6% (± 1.5), 0.7 % (± 2.3) and 1.3 % (± 1.4) from alanine, film and local ionisation chamber measurements respectively. Although these levels of discrepancy are within the measurement uncertainty, all the cases with greater than 2% difference underwent a detailed analysis of root cause. It was found that dose distributions in the treatment plan for these cases were less homogenous, such that they had up to a 2.2% standard deviation of dose within a 5 mm² area (figure 4 is giving a comparison of dose profile across the active volume of ionisation chamber calculated by the TPS and measured by alanine and silica beads). Setup variation between the silica beads and alanine measurements may therefore be the main contributing factor to these larger differences. This may have happened due to placement and removal of the film.

By looking at the histogram of comparison between silica bead results and measured values by other detectors/TPS calculation, in fig. 3, the positive value of mean percentage differences may suggest that, like other silicon based detectors [27, 28] the silica beads slightly over respond (0.6% on average compared to alanine in this study). This was also noticed in previous work, [16, 17]. However, all the values are within measurement uncertainty and so it is not possible to form a firm conclusion. The density of silica beads is less than that of diodes [15], which are routine dosimeters for clinical dosimetry [29], hence if there is over response it is expected to be much less than that of the diodes which is reported by Huang et al. [30].

The range of doses used by the centres in this audit varied from approximately 15 to 27 Gy. The large dynamic dose range of silica bead is particularly advantageous in these circumstances, compared to other well-established TLD materials, such as 1 mm³ LiF: Mg, Ti cubes, which are designed for conventional radiotherapy dose range with an upper dose range limitation of 10 Gy. The independence of the silica bead dose response to beam angle and dose rate is of importance in diverse delivery techniques as used in this study and compares favourably with other detectors such as diamond detectors and ionisation chamber 2D-arrays with a dose rate and directional dose response [10, 31, 32].

Along with these encouraging results, the inert nature and low fading of these silica bead TLDs suggest that they may be a suitable tool for postal dose audits without concerns regarding the temperature, humidity and handling conditions that an audit parcel may experience. When a large number of TL dosimeters for such applications are required a further advantage is the low cost and ease of availability. The small size and inert nature of them is also of particular interest for possibility of using them as in-vivo dosimeters which is part of our future work.

5. Conclusions

The silica beads have been evaluated for their use in postal dosimetry audit by undertaking a feasibility study alongside an audit conducted at 20 radiotherapy centres within the UK assessing positional and dosimetric accuracy of SABR lung treatment delivery. Their performance has been compared to alanine, ionisation chamber and film dosimeters and doses predicted by the treatment planning systems and agreed well with the above-mentioned dosimetry systems. Dosimetric properties including linear response over a wide range of doses, low fading, dose rate and angular independency in addition to their reusability, chemically inert nature and low cost is advantageous for their application in postal dosimetry services. The results therefore confirm the potential of the silica bead TLD systems as dosimeters for postal audit for such techniques as SABR.

The results are encouraging and their application in postal dosimetry services is an example where the low fading, non-hygroscopic nature and robustness is important where irradiation and postage return may take some time. In particular, where more complex dose distributions and field arrangements may be required to be measured [9, 12].

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Highlights:

- Silica beads have been used as novel micro-TLDs in a national dosimetry audit across UK
- The performance of the TLDs assessed in non-equilibrium conditions near tissue/lung interfaces
- TLDs' Results agreed well with those obtained from alanine, film and ionisation chamber detectors