Reports of Practical Oncology and Radiotherapy 25 (2020) 35–40

Available online at www.sciencedirect.com

Reports of Practical Oncology and Radiotherapy

journal homepage: http://www.elsevier.com/locate/rpor

Original research article

In vivo monitoring of total skin electron dose using optically stimulated luminescence dosimeters

Tanya Kairn[a,b,*], Rachael Wilks[a,b], Liting Yu[a,b], Craig Lancaster[a], Scott B Crowe[a,b]

[a] Cancer Care Services, Royal Brisbane and Women's Hospital, Herston Qld, Australia
[b] Science and Engineering Faculty, Queensland University of Technology, Brisbane Qld, Australia

ARTICLE INFO

Article history:
Received 12 July 2019
Received in revised form
23 September 2019
Accepted 9 December 2019
Available online 16 December 2019

Keywords:
Radiation therapy
Electron radiotherapy
In vivo dosimetry
Skin dose

ABSTRACT

Aim: This study retrospectively analysed the results of using optically stimulated radiation dosimeters (OSLDs) for in vivo dose measurements during total skin electron therapy (TSET, also known as TSEI, TSEB, TSEBT, TSI or TBE) treatments of patients with mycosis fungoides.
Background: TSET treatments are generally delivered to standing patients, using treatment plans that are devised using manual dose calculations that require verification via in vivo dosimetry. Despite the increasing use of OSLDs for radiation dosimetry, there is minimal published guidance on the use of OSLDs for TSET verification.
Materials and methods: This study retrospectively reviewed in vivo dose measurements made during treatments of nine consecutive TSET patients, treated between 2013 and 2018. Landauer nanoDot OSLDs were used to measure the skin dose at reference locations on each patient, as well as at locations of clinical interest such as the head, hands, feet, axilla and groin.
Results: 1301 OSLD measurements were aggregated and analysed, producing results that were in broad agreement with previous TLD studies, while providing additional information about the variation of dose across concave surfaces and potentially guiding future refinement of treatment setup. In many cases these in vivo measurements were used to identify deviations from the planned dose in reference locations and to identify anatomical regions where additional shielding or boost treatments were required.
Conclusions: OSLDs can be used to obtain measurements of TSET dose that can inform monitor unit adjustments and identify regions of under and over dosage, while potentially informing continuous quality improvement in TSET treatment delivery.

1. Background

This study investigated the use of optically stimulated radiation dosimeters (OSLDs) for in vivo radiation dose measurements during electron radiotherapy treatments of patients with mycosis fungoides. Mycosis fungoides is a chronic and progressive form of cutaneous T-cell lymphoma, which causes rashes, tumours and other skin lesions that can spread to cover the entire body.[1] Total skin electron therapy (TSET, also known as TSEI, TSEB, TSEBT, TSI or TBE) is a-well established treatment for mycosis fungoides,[2–4] which can produce high rates of complete or partial response with low toxicity.[1,5]

Many challenges associated with TSET treatments arise from the need to treat the patient in a series of standing poses (either on a rotating platform[6,7] or using the six-pose Stanford technique[3]), in order for the radiation beams to cover the whole of the patient's skin. Images of the patient in their standing positions cannot be obtained using conventional computed tomography (CT) imaging systems.[8] This limits the usability of computerised radiotherapy treatment planning systems. Instead, manual correction-based dose calculations are performed to identify the number of monitor units (MU) required to deliver the prescribed dose to the patient's skin.[9] In vivo dosimetry measurements can then be performed during treatment, to verify those manual dose calculations,[9,10] check for possible dosimetric effects of changes in patient stance[11] and identify regions requiring additional shielding or boost treatments.[12,13]

There is a substantial literature on the use of thermoluminescent dosimeters (TLDs) to perform in vivo dose measurements during TSET treatments.[10] For example, Anacak et al.[14] and Antolak et al.[13] each reported retrospective studies where in vivo TLD measurements were performed on more than 60 patients

* Corresponding author.
E-mail address: t.kairn@gmail.com (T. Kairn).

https://doi.org/10.1016/j.rpor.2019.12.011
1507-1367/

and results were generally within 10% of the prescribed dose at reference locations,[13,14] while over-doses of up to 60% and under-doses of up to 99% were measured at dosimetrically challenging locations.[13] TLD measurements have also been used to investigate newer TSET delivery techniques, such as the use of single electron fields (rather than paired electron fields),[12] the use of a platform to rotate the patient during beam delivery,[6,15] and the treatment of anaesthetised paediatric patients.[16] Guidi et al's review of the literature on in vivo dosimetry for TSET treatments also referred to several studies that used MOSFET dosimeters and radiochromic film,[10] as well as one study that reported diode measurements performed on 360 patients treated using electron beam radiation delivered to lesions at various anatomical sites.[17] The use of glass beads as alternative TLDs has also been reported, specifically for TSET dosimetry.[18]

By contrast, the literature on the use of optically stimulated luminescence dosimeters (OSLDs) for this purpose is limited.[10] Bao et al. used OSLDs to verify the dose distributions from two TSET treatments delivered to infants,[19] but other published studies relating to the use of OSLDs to measure radiotherapy treatment dose have been largely focused on phantom-based proof-of-concept measurements.[20,21]

While both OSLDs and TLDs are advantageous for in vivo use, due to their small size, re-usability and lack of reliance on the cabling and electronics required by MOSFETs or diodes, OSLDs have several additional advantages over TLDs. OSLDs are read out using exposure to light rather than heat and so OSLD readout can be completed more quickly and easily than TLD readout,[22] using a lightweight optical reader rather than a controlled heating system. OSLD response is linear with dose, stabilises quickly (within an hour) and is thereafter subject to minimal fading.[23,24] In recent years, OSLDs have begun to replace TLDs in several areas of radiotherapy dosimetry, including personal radiation dose monitoring,[25,26] postal audits of radiotherapy beam calibration,[22,27] assessments of linac head leakage[28,29] and dose measurements during photon radiotherapy treatments.[20,30] Despite all this, a comprehensive evaluation of the results obtainable by using OSLDs for in vivo dosimetry of TSET treatments has yet to be reported in the literature.

2. Aim

This study, therefore, used a retrospective analysis of in vivo OSLD measurements performed during TSET treatments at one institution, as a means to aggregate and evaluate the information that can be obtained from such measurements and, thereby, establish the usefulness of OSLDs for this purpose, confirm the importance of continuing to measure TSET treatment dose, and provide guidance for managing OSLD-based in vivo dosimetry services.

3. Materials and methods

This study retrospectively reviewed in vivo dose measurements made during treatments of nine consecutive TSET patients, treated between 2013 and 2018, after the implementation of an OSLD-based in vivo dosimetry programme[31] in a radiation oncology department that had been delivering TSET treatments since the mid-1980s.[2]

All nine patients were treated using a modified Stanford technique, using paired electron fields to treat patients in six standing positions, supported by a wooden frame, behind a 0.6 cm-thick Perspex spoiler (diagrams of the treatment setup can be found in references [3] and [9]). For all treatments, the distances from the radiation isocentre to the spoiler and the support frame were maintained at a constant 249 and 300 cm, respectively. Each patient was centred in the support frame, as consistently as possible. For this treatment geometry, the optimal gantry angles for the paired electron beams were determined via ionisation chamber measurements to be 72.1° and 107.7°; these gantry angles were used for all patient treatments.

All patients had small sheets of film-coated lead applied to cover and shield their eyes, finger- and toe-nails and nailbeds, for the duration of their treatments. Additional shielding was then applied after the start of treatment, where necessitated by the results of in vivo dose measurements.

Treatments were planned using a manual correction-based method which related the dose from an uncollimated high-dose-rate 6 MeV electron beam at the prescription depth in the patient to the dose from a standard 6 MeV electron beam under conventional reference conditions. This method produced a prediction of the number of MU required to deliver the prescription dose to each patient. The validity of the MU calculation for each patient was tested at each treatment cycle, firstly by performing ionisation chamber measurements to check the consistency of the linac's output and secondly by performing in vivo dose measurements with OSLDs placed on the patient's skin to evaluate the dose delivered to the patient.

To perform these in vivo measurements, up to one hundred Landauer nanoDot OSLDs (Landauer Inc, Glenwood, USA) were calibrated in advance, by irradiating the entire batch to 2 Gy and using the resulting measurements to derive a specific element correction factor[32,33] for each OSLD in the batch. All OSLD measurements were read out using a Landauer micoStar reader with InLight software (v 4.3) (Landauer Inc, Glenwood, USA). Between measurements, signal was cleared from the OSLDs using a 3 h bleaching cycle[24] in a Gammasonics Manual OSL Annealing Lightbox (Gammasonics Institute for Medical Research, Lane Cove, Australia).

In vivo dose measurements at reference locations (on the chest, abdomen, upper and lower back) were used to verify the suitability of the calculated treatment MUs for achieving the prescribed dose for each patient, and to check for effects on dose from changes in patient stance. Each reference measurement was the average result from two OSLDs.

Measurements at non-reference locations were also used, for most patients, to investigate the need for either additional shielding or additional boost fields. Additional measurements at non-reference locations were used to evaluate dose in anatomical regions of particular interest to the prescribing oncologist and treatment team. While the reference measurement locations were all on planar surfaces, many of these non-reference locations were on irregular surfaces, such as the ears, fingers and toes, overhangs such as the chin, breasts and belly, and concave surfaces such as the axilla and groin. Examples of these non-reference locations are shown in Fig. 1.

Before being taped to the skin, each OSLD was covered in cling film (to prevent tape sticking to the identifying labels on the OSLD housing) before being covered in tape and labelled with an identification number that was traceable to the patient, position and treatment date. Due to the symptoms of mycosis fungoides and the skin's response to radiation, particular care was needed when placing the OSLDs on each patient and removing them after treatment, to avoid causing additional pain or discomfort to the patient. For this reason (in addition to the time required to place and remove the OSLDs and analyse each measurement), the number of measurement locations was generally limited to those that were specifically requested or required to verify the safety and accuracy of the treatment.

This retrospective review of OSLD measurement data, MU calculation records and other treatment records was characterised as an ethics-exempt quality assurance project, by the Royal Brisbane and Women's Hospital Human Research Ethics Committee. All patients

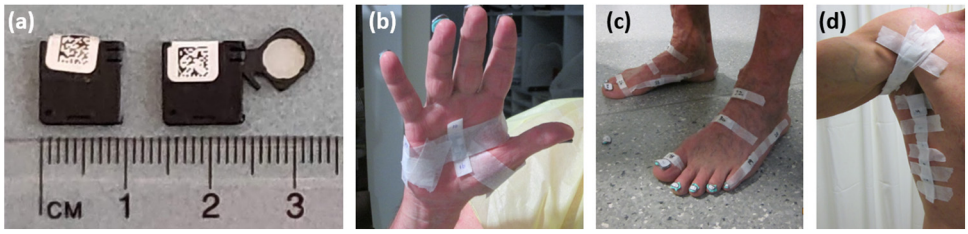

Fig. 1. (a) Photograph of OSLD chip (white circle) inside and outside plastic housing (black square). Photographs of OSLDs in non-reference locations on patients: (b) hand, (c) foot (showing toenail shielding) and (d) axilla.

Table 1
Numbers of measurements per patient, in different anatomical regions, summed over all treatment cycles.

Anatomical region	Patient 1	Patient 2	Patient 3	Patient 4	Patient 5	Patient 6	Patient 7	Patient 8	Patient 9
Reference	12	25	12	14	40	60	39	20	24
Non-reference thorax		4	2		20	8	8		8
Non-reference abdomen		7							
Waist	7	21	20		50	61	26	15	32
Hips	2	4						2	
Groin		1		1					1
Head	8	5	6	20	18	34		8	1
Neck		5	7		4	4	8		
Shoulders	2	2			6				5
Axilla				18	12	10		2	3
Upper arm					14	8			
Elbow	10	4	2		4				2
Forearm		8			16	4			4
Wrist			8				2		
Hand	58	28	18		12	14	12	4	10
Upper thigh	4		8		10	10		6	7
Mid thigh	2	10			8				
Knee	4	3			6				4
Lower leg	2	8			8				4
Ankle	3			3	14	18			8
Foot	54	20	10	13	18	24	18	4	9

Table 2
Effects of in vivo dose measurements on treatment delivery.

Patient	Total dose	No. cycles	Cycles before adjustment	Result	Recorded reason	Shielding added	Boosts
1	30 Gy	15	3	11% low			
2	30 Gy	12	5 then 7	(dose reduced by 8%, twice)	(Excessive skin reaction)		L&R axilla, L&R groin, scalp
3	32.5 Gy	12	6	10% high			
4	35 Gy	14	2	3.5% high		Hands & feet (25–30% high), forearms	L&R axilla, L&R groin, scalp
5	20 Gy	10	1	13% low	Change in stance	Hands & feet & ears	
6	32 Gy	16	1	14% low	Change in stance	Feet (20% high)	L&R axilla, L thigh
7	32 Gy	16	1 then 4	16% low then 5.7% high	Change in stance, then stabilised		
8	12 Gy	6	2	10% low			L arm, L&R thighs
9	12 Gy	6		No change			

had given informed consent for their data to be used for research. The study was completed in accordance with the Declaration of Helsinki.

4. Results

Table 1 provides a summary of the number of different OSLD measurements that were recorded for each patient, in different anatomical regions. The total number of measurements contributing to this study was 1301, of which 246 were measured in reference regions (anterior thorax, posterior thorax, anterior abdomen, posterior abdomen) and the remaining 1055 were measured in a range of non-reference regions. The total number of measurements per patient ranged from 64 to 262 and the total number of measurements per treatment cycle ranged from 7.8–20.3. Only one patient received fewer than 1 reference measurement per cycle (with measurements stopping before the end of the treatment, after the MU needed to deliver the prescription were identified), with the other patients receiving between 1 and 4 reference measurements per cycle. All patients received between 44 and 222 non-reference measurements, although these measurements were performed sporadically according to clinical need. No patient received the same non-reference measurements at every treatment cycle.

The results of these in vivo dose measurements, in terms of their effect on subsequent treatment delivery (changes to MU, addition of shielding) are summarised in Table 2. Treatment MU were adjusted in response to the reference OSLD measurement results in all except 2 cases, to compensate for dose differences of 3.5%–16% that resulted from changes in patient stance between treatment

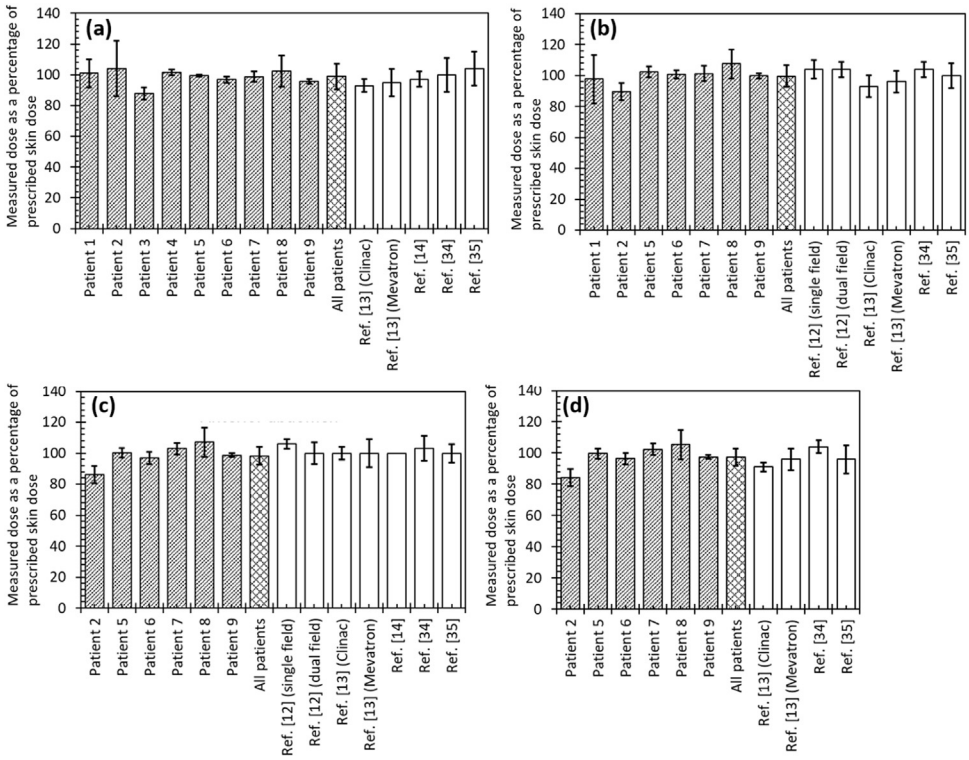

Fig. 2. OSLD measurement results shown alongside previous TLD measurement results, for reference locations on the (a) anterior thorax, (b) anterior abdomen, (c) posterior thorax and (d) posterior abdomen.

Table 3
Summary of non-reference dose results, as a percentage of prescribed skin dose (mean, with first standard deviation in brackets).

Anatomical region	This study	Ref. 32	Ref. 13 (Clinac)	Ref. 13 (Meva-tron)	Ref. 14(4 mm spoiler)	Ref. 14(10 mm spoiler)	Ref. 12 (single field)	Ref. 12 (dual field)
Cranial vertex	72 (4)	85 (26)	87 (20)	76 (21)	79 (29)	92 (22)	75 (11)	113 (24)
Forehead	94 (3)	103 (7)		96 (8)			103 (7)	118 (8)
Post neck	97 (24)			103 (6)			101 (6)	104 (8)
Shoulder	90 (13)		74 (8)	67 (15)	92 (7)	94 (18)	89 (11)	87 (12)
Hip	94 (7)	100 (12)						
Axilla	70 (28)	75 (28)	60 (25)	59 (19)			90 (28)	109 (14)
Perineum	16 (7)	32 (22)		25 (21)				
Inner thigh	42 (37)	109 (24)	59 (23)	54 (25)			68 (34)	63 (25)
Under breast	23 (21)	40 (40)						
Palm of hand	89 (30)	81 (10)			54 (19)	55 (18)	87 (11)	84 (14)
Back of hand	79 (21)	84 (17)	85 (6)	88 (7)				
Sides of hand	113 (34)							
Elbow	88 (25)		90 (13)		78 (18)	67 (14)		
Inner elbow	76 (20)							
Outer elbow	114 (10)							
Mid. thigh	88 (12)			96 (12)			93 (3)	95 (5)
Knee	103 (12)				94 (8)	90 (6)		
Lower leg	96 (10)	104 (16)						
Ankle	100 (14)	97 (5)						
Top of foot	116 (10)		117 (7)	124 (9)	110 (10	91 (10)	85 (13)	117 (14)

planning and delivery. One of the remaining cases required no adjustment and the other was adjusted at the prescribing oncologist's request, to limit the progression of an "excessive skin reaction". The non-reference measurements led to the addition of shielding in 3 of the 9 cases, and the use of subsequent boost fields in 4 of the 9 cases.

Data in Figs. 2(a–d) show that mean doses measured at reference points on planar surfaces were similar to doses measured using TLDs in several previously published TSET studies.[7,12–14,34,35] In Figs. 2(a–d), the results of the measurements at reference locations are shown separately for each of the nine patients in this study, to provide an indication of the degree of variability that was observed between individuals, for these comparatively straightforward measurements.

Doses measured on relatively planar surfaces, around the patients' waists were consistent and agreed with the prescription within a standard deviation of 7.6% and a second standard deviation of 14.2% (see Fig. 3). The consistency of the OSLD measurements made around the patients' waists also compared favourably with published results for patients treated using a rotational TSET method; Piotrowski et al.[35] and Hensley et al.,[15] respectively, reported doses that were consistent within +/− 16% around the abdomen and within +/−10% around the trunk.

Data in Table 3 indicates that doses measured on convex surfaces (cranial vertex, forehead, posterior neck, shoulder and hip) were

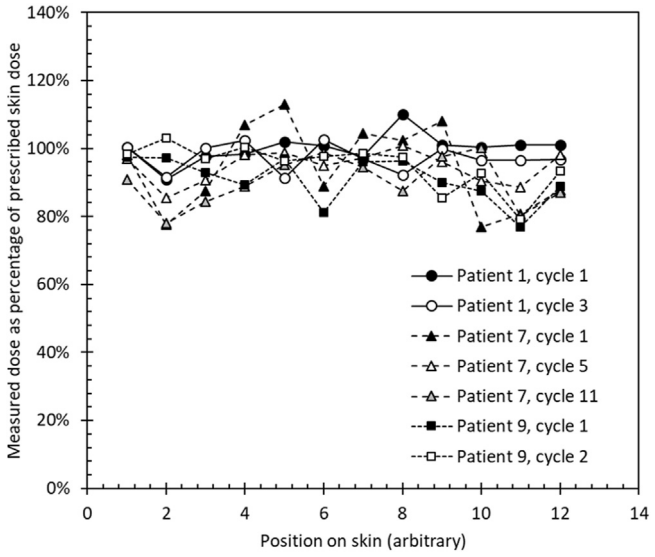

Fig. 3. OSLD measurements at non-reference locations around the patients' waists.

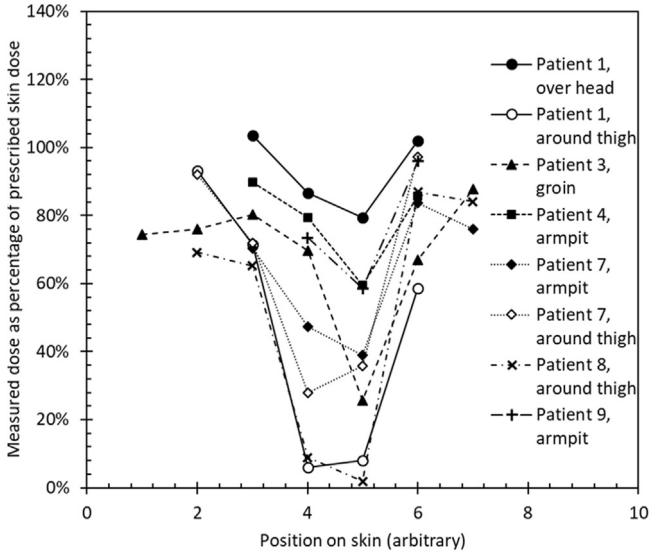

Fig. 4. OSLD measurements at non-reference locations of expected under-dose.

also similar to doses measured in previous studies that used TLDs. Doses measured using OSLDs on the forehead were more consistent, and doses measured using OSLDs on the back of the neck were less consistent than the doses measured in previous TLD studies, although mean OSLD measurements in both locations were within 10% of the prescription dose. OSLD measurements showed a mean dose depletion of 28% at a point on the top of the head (cranial vertex), which is similar to the mean dose depletions of 13%–25% that were measured on the top of the head in several previous TLD studies.[12–14,34]

Results for patients where OSLD measurements were performed at a series of points under the axilla and perineum and over the top of the head are shown in Fig. 4. Regions of under dosage were often mitigated by delivering a follow up treatment using conventional electron or photon boost fields (see Table 1). The results for patients where OSLD measurements were made at a single worst-case point on the axilla, perineum and inner thigh are shown in Table 3. Here, the dose depletions measured with OSLDs are in general agreement with previous TLD measurements,[12–14,34] with the exception that Chen et al. measured some dose enhancements in the armpits and Weaver et al. measured some dose enhancements at the inner thigh.[14,34] These results provide an indication of the extent to which dose to these anatomical regions can be affected by variations in patient anatomy and setup.

Table 3 also lists OSLD measurements on limbs and extremities that suggest there may be potential for improvements in treatment setup, to improve dose homogeneity during these treatments. For example, doses exceeding the prescription by up to 30% were measured along the sides of the hands, whereas doses measured on the palms and backs of the hands were often measured as substantially lower than the prescription dose. There was a similar difference between the doses measured on the inner and outer elbow (lower and higher doses, respectively). These trends suggest that some changes to the local hand and arm positioning protocol may be advisable in addition to some refinement of the practice of shielding the entire hand when localised over-doses are detected.

5. Conclusions

OSLDs can be used to obtain measurements of TSET dose that can inform treatment MU adjustments and identify regions of under and over dosage. Analysing these results on a case by case basis leads to the frequent use of shielding and boosts and it is, therefore, necessary to ensure optimal treatment of each patient. Additionally, the aggregation of measurement data and analysis of trends provides an opportunity to refine treatment setup practices, for the benefit of the entire patient population. The consistent use of a specific set of measurement points is advisable, to increase the value of future in vivo measurement data, as an audit and quality improvement resource.

Financial disclosure

None declared.

Conflicts of interest

None declared.

Acknowledgement

The authors wish to thank the physicists at the Royal Brisbane and Women's Hospital who performed, analysed and reported OSLD measurements for TSET treatments over the last five years.

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