GeB Flat Fibre TL dosimeters for *in-vivo* measurements in radiosurgery

Amjad Alyahyawi [1,2*], Alexis Dimitriadis[3], Andrew Nisbet[4], D. A. Bradley[2,5]

[1]Department of Diagnostic Radiology, College of Applied Medical Sciences,
University of Ha'il, Ha'il, Saudi Arabia
[2]Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom.
[3]Queen Square Radiosurgery Centre, National Hospital for Neurology and Neurosurgery, UCLH, London
[4]Department of Medical Physics and Biomedical Engineering, University College London, UK.
[5]Sunway University, Centre for Biomedical Physics, Jalan Universiti 47500 Subang Jaya, Malaysia.

Abstract:

Noting an increase in demand for procedures involving clinical radiosurgery we seek to develop a high spatial resolution thermoluminescence dosimeter (TLD) to allow conduct of *in vivo* dose verification measurements. An associated need is for a dynamic dose range exceeding that of the well-established LiF (Mg,Ti) phosphor TLD-100, with in particular the latter being limited in performance at the elevated doses seen in radiotherapy. The work investigates the performance of a novel GeB co-doped Flat Fibre (GeB-FF) fabricated using the modified chemical vapour deposition (MCVD) process, the hollow capillary optical fibres (COF) produced from this being collapsed down into flat fibres (FF) to create strain-related defects. This process has already been demonstrated to increase the low dose sensitivity of optical fibres, notably at diagnostic x-ray potentials, with Minimum Detectable Dose (MDD) values of down to 0.1 μGy. The intent of present work, conducted as a component of a safety audit, part of the hospital periodic radiation protection quality assurance program, has been to examine and compare the performance of the two forms of TL dosimeter, GeB-FF and TLD-100, measuring scattered radiation resulting from cranial cavity radiosurgery procedures. The dosimeters were placed on the neck, chest and pelvis of 20 patients. Using both types of dosimeter, raw dose values at each site show general accord ($\pm$ 3 mGy at 1 σ), covering mean doses ranging from some 10 mGy to less than 1 mGy, representing doses of < 1% to < 0.1 % of prescribed dose at the treatment site. GeB-FF results uncorrected for energy response show absorbed doses greater than that using TLD-100, by factors of some 1.4, 1.2 and 1.5 for the pelvis, chest and neck respectively; energy corrections have been shown elsewhere to provide for much closer agreement.

Keywords: glass dosimeters; stereotactic radiosurgery; GeB flat fibres.

* Corresponding Author a.alyahyawi@surrey.ac.uk

1. Introduction:

In recent years stereotactic radiosurgery (SRS) has become increasingly popular, with a number of medical machines now able to provide for such medical procedures (O'Beirn et al., 2018). Examples include Gamma Knife, a robotic linear accelerator-based system and CyberKnife (Alyahyawi et al., 2017). SRS provides precise fine-beam delivery of high radiation dose that can reduce the number of treatment sessions. The SRS technique is used to treat brain tumours, trigeminal neuralgia and other intracranial disorders. In SRS, the doses that are used vary in accord with the size of the lesion (up to 2 cm: 22-25 Gy) (Nieder et al., 2014).

Despite the various developments in methods that have taken place following establishment of the SRS technique, more attention needs to be given to the scattered radiation received by the organs at risk (Ma, 2019). A previous multi-centre dosimetric audit was carried out by Alyahyawi et al. (2019), investigating scattered dose to the lens of the eye during SRS procedures, use being made of three types of dosimeter (Ge-optical fibres, glass beads and TLD-100). The study was performed as a result of recommendations to reduce the risk of lens opacifications, seeking limitation of the dose to the lens (ICRP, 2012); the results indicated that the doses were below the new threshold of 0.5 Gy.

Concerning the above, several studies have investigated the potential use of doped-silica dosimeters as passive detectors, detailing the detection of several types of ionizing radiations in medical applications, including photons (Yaakob et al., 2011; Abdul Rahman et al., 2011; Issa et al., 2012); electrons (Hashim et al., 2009); protons (Hashim et al., 2006), alpha particles (Ramli et al., 2009) and; neutrons (Hashim et al., 2010). Further studies have involved use of different medical techniques such as intensity-modulated radiotherapy (IMRT) verification (Noor et al., 2010), brachytherapy dosimetry (Issa et al., 2012; Palmer et al., 2012), and interface radiation applications (Abdul Rahman et al., 2011). Investigations have further been carried out on undoped flat fibres (Abdul Sani et al., 2014) and doped flat fibres (Nawi et al., 2015; Begum et al., 2015). In regard to detection limits, in studies of clinical diagnostic X-ray dosimetry, Alyahyawi et al. (2018) determined minimum detectable doses (MDDs) of 0.1 μGy and 1.0 μGy for GeB co-doped flat fibres (FF) and Ge-doped discs respectively. These low levels of detection benefit strongly from the photoelectric effect. Conversely, Ghomeishi et al. (2015) in investigation of 6 MV photons found an MDD for Ge-doped flat fibres of 31 ± 8 mGy.mg (equivalent to some 62 mGy), largely a result of the less powerful Compton scattering dependencies. For intraoperative radiotherapy Moradi et al. (2019) reported a minimum detectable dose for Ge doped fibres of around 50 mGy. Other than the predominant interaction mechanisms, the MDD also depends on a range of other factors, including type of dopant and concentrations, also the means of fabrications of the fibre. In the work herein, with GeB co-doped flat fibres (FF) showing MDDs that are well-suited to present interests, use has been made of these in probing SRS scattered doses.

In SRS procedures, small uncertainties linking to small field profile measurements can result in systematic errors at magnitudes of concern (Lam et al., 2020). The measurement challenges include detector size, positioning issues, and the absence of charged particle equilibrium conditions. Of the dosimeters used in SRS dosimetry, these include diamond detectors and small volume ionisation chambers, limitations from penumbra broadening requiring significant corrections in some cases. Notwithstanding the high spatial resolution and accurate measurement offered by diamond detectors, positioning issues and dose-rate corrections arise (Pappas et al., 2008). Real-time dosimetry is also being used in SRS; particularly highlighted is an integral quality monitor (IQM), with an area integrating energy fluence-monitoring sensor (AIMS) typically mounted between the beam shaping and collimation system and the patient (Qian et al, 2015).

In present study, surface measurements have been carried out on 20 patients, being children of various ages, all suffering from different brain lesions at the time of treatment. Specifically, investigation was made of scattered radiations doses to the thyroid, chest and pelvis during SRS treatment. It is to be noted that this work was conducted as a component of an approved safety audit, part of the hospital periodic radiation protection quality assurance program.

2 *Materials and methods:*

2.1 *Sample preparation:*

Use has been made of GeB-FF and TLD-100. The Ge-B-doped flat fibres were fabricated using the process of modified chemical vapour deposition (MCVD) (Dambuli et al., 2012). The 0.3mm thick GeB-doped flat fibre samples were manually cut into 3.5 ± 0.1 mm lengths, giving rise to a mean mass of 0.002g. For the TLD-100, use has been made of TLD-100 discs of diameter 9.1 ± 0.1 mm, thickness 0.4 ± 0.01 mm and mean mass 0.5 g. In order to obtain a set of dosimeters of approximate uniform response a screening process was performed. For this, the complete set of dosimeters were simultaneously irradiated to a dose of 1 Gy delivered by a linear accelerator operating at 6 MV (a Varian TrueBeam STX linear accelerator unit) located at the Royal Surrey County Hospital. Samples providing a uniform response to within ± 4% of the mean TL yield were selected for use.

2.2 *Annealing and readout:*

In regard to TL dosimetry, sample annealing prior to irradiation is needed, removing residual filled traps arising from previous use or handling (Alyahyawi et al., 2016). The process begins with the placing of the dosimeters on an aluminium plate, then wrapped with aluminium foil and placed in an oven (in this case a Carbolite oven, U.K), annealed at 400 °C for a period of 1 hour. Post-annealing, the samples were left inside the oven to allow slow cooling to room temperature, stabilizing the traps. Subsequently, prior to use and post-irradiation through to readout, the dosimeters were kept in light-tight containment at room temperature, preventing exposure to visible light, humidity and temperature variation. For readout, a Harshaw model 4500 TLD reader supported by WinREMS software was employed. The time-temperature profile (TTP) comprised an initial ramp to 160° C for 15 s, then an acquisition temperature of 300° C for 30 s. In order to inhibit sample oxidation all measurements were obtained in a nitrogen atmosphere. For each dosimeter the observed TL yield was normalized to unit mass of the particular TL medium, obtaining results in μC/g. The selection of the particular annealing regime has been discussed in Alyahyawi (2019). A typical glow curve for the GeB flat fibre is shown in Fig. 1, again characterised in detail in Alyahyawi (2019).

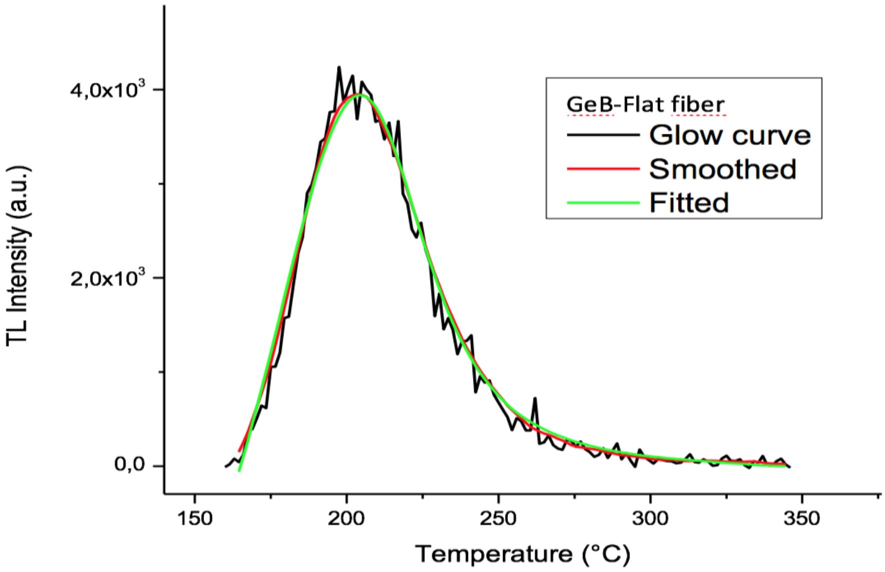

Figure 1. A typical glow curve for the GeB flat fibre, characterised in detail in Alyahyawi (2019).

2.3 Calibration:

For calibration, irradiations of both the GeB-flat fibre and TLD-100 were performed using the same Varian TrueBeam STX linear accelerator as before, operated at 6 MV. The samples were irradiated to doses from 20 mGy to 0.5 Gy, delivered at a dose-rate of 600 MU/min, use being made of a 10 x 10 cm field size at a source to sample distance (SSD) of 95 cm and with the samples at 5 cm depth in *solid water*^{TM} . Results for both the GeB-flat fibre and TLD-100 are shown in Figure 2.

2.4 Irradiation procedure using a radiosurgery machine:

Use has been made of a Gamma Knife Perfexion (Elekta AB, Stockholm, Sweden), a ^{60}Co source system of mean energy 1.25 MeV, delivering dose-rates of between 2.5 to 3 Gy min^{-1}, located at the National Hospital for Neurology and Neurosurgery in London (UK). Five samples from each dosimeter were kept in small plastic bags to then be placed on the skin surface of each patient during the SRS treatment. For each patient, three plastic bags were used, with one placed at each location: the thyroid, chest and pelvis. A fourth bag was kept as a control to account for the background signal.

3. Results and discussions:

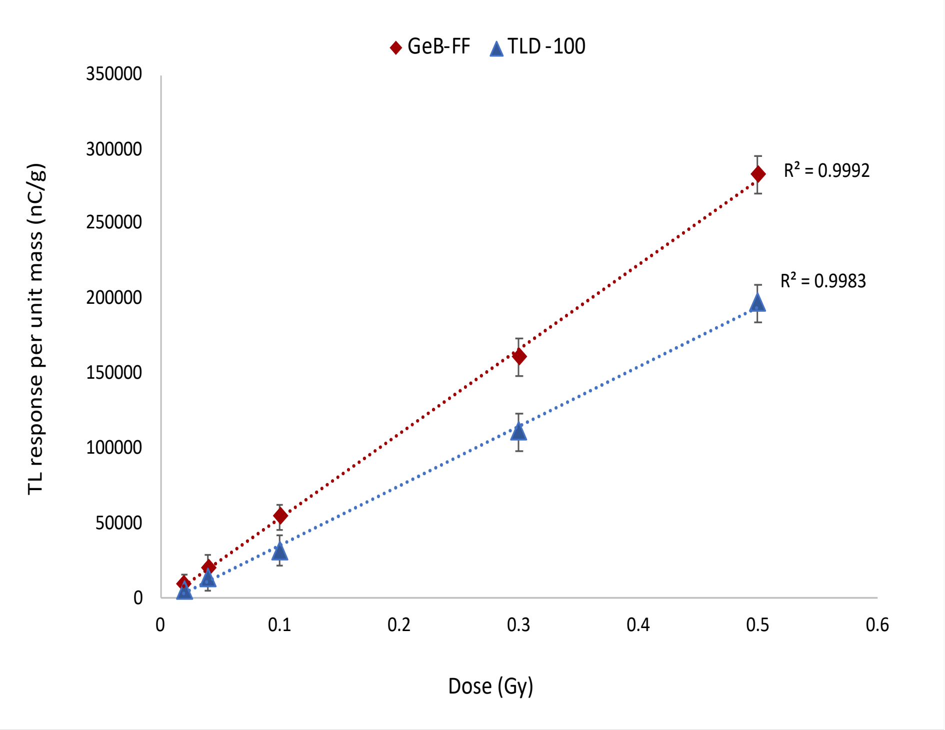

Fig. 2. Calibration curve for doses from 20 mGy to 0.5 Gy, with use made of a Varian TrueBeam STX linear accelerator

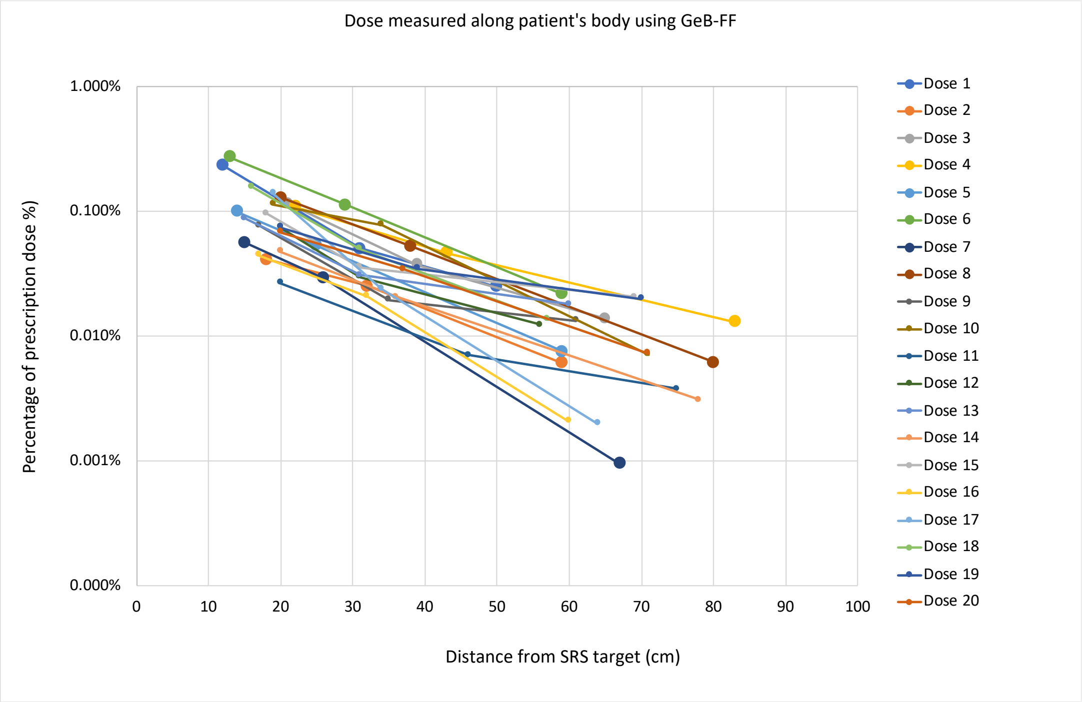

Fig. 3. Percentage of prescription dose versus the distance from SRS target, with use made of GeB-FF.

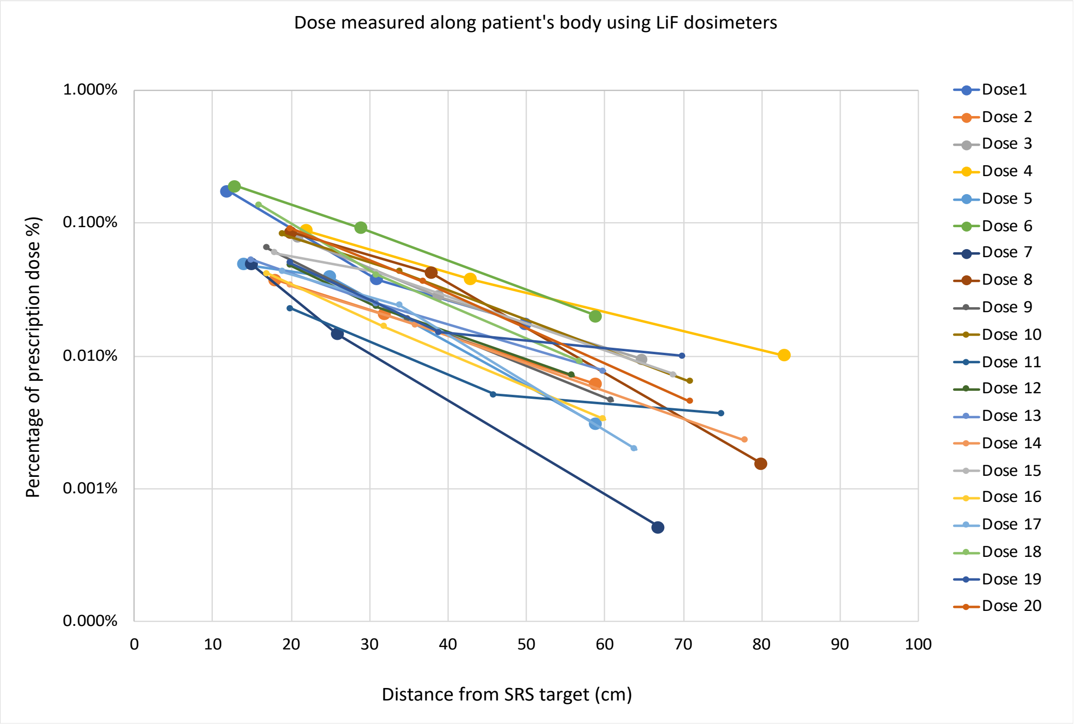

Fig. 4. Percentage of prescription dose versus the distance from SRS target, with use made of TLD-100.

In use of both forms of dosimeter, the results indicate the same patterns being obtained (Figures 3 and 4), validating in good part use of the GeB-FF for the particularly demanding task of measuring scattered dose in SRS applications. The highest readings for the absorbed dose from scattering were obtained for the thyroid, followed by the chest and pelvis. Using both types of dosimeter, raw dose values at each site show general accord (± 3 mGy at 1 σ), covering mean doses ranging from some 10 mGy down to less than 1 mGy, representing doses of < 1% to < 0.1 % of prescribed dose at the treatment site. The readings obtained from use of the GeB-FF have been seen to exceed that from use of the TLD-100 by on average a factor of 1.4, photoelectric absorption interactions taking place more predominantly in the silica media than in the LiF based TLD-100. Energy dependence corrections bring both evaluations into line, as previously shown in Alyahyawi et al. (2019).

4. Conclusion:

The work has sought to measure the scattered doses to thyroid, chest, and pelvis during radiosurgery treatment using novel silica material GeB-FF and LiF based TLD-100. Use has been made of a Gamma Knife Perfexion facility (Elekta AB, Stockholm, Sweden) at the National hospital for Neurology and Neurosurgery in London. The measurements were obtained for 20 children undergoing SRS radiosurgery treatment in respect of a number of brain lesion types, the work being conducted as a component of an approved safety audit, part of the hospital periodic radiation protection quality assurance program. The results showed the readings to be greatest at the level of the thyroid, this location being closest to the SRS target. The results showed similar results for both materials with relatively small variations of 1.4, 1.2 and 1.5 for the pelvis, chest and neck respectively, the difference relating to the energy dependence of the silica materials, to be accounted for in calibration. The GeB-FF offer versatility in terms of both dose sensitivity, robust in moist environments such as can be expected to be experienced in skin dose evaluations.

Acknowledgement:

The authors extend their appreciation to the University of Ha'il, University of Surrey, Sunway University, and the Royal Surrey County Hospital for supporting this research.

5. References:

Abdul Rahman, A.T., Nisbet, A. & Bradley, D.A., 2011. Dose-rate and the reciprocity law: TL response of Ge-doped SiO2 optical fibers at therapeutic radiation doses. *Nuclear Instruments and Methods in Physics Research, Section A:* 652, 891–895.

Abdul Sani, S.F., Alalawi, A.I., Azhar A.R, H., Amouzad Mahdiraji, G., Tamchek, N., Nisbet, A., Maah, M.J. & Bradley, D.A., 2014. High sensitivity flat SiO_2 fibres for medical dosimetry. *Radiat. Phys. Chem.*, 104, 134–138.

Alyahyawi, A., Jupp, T., Alkhorayef, M. & Bradley, D.A., 2018. Tailor-made Ge-doped silica-glass for clinical diagnostic X-ray dosimetry. *Appl. Radiat. Isot*. 138:45-49.

Alyahyawi, A., Dimitriadis, A., Jafari, S.M., Lohstroh, A., Alanazi, A., Alsubaie, A., Clark, C.H., Nisbet, A., Bradley, D.A., 2019. Thermoluminescence measurements of eye-lens dose in a multi-centre stereotactic radiosurgery audit. *Radiat. Phys. Chem.*, 155, 75–81. Available at: https://doi.org/10.1016/j.radphyschem.2018.08.030.

Alyahyawi, A., Jupp, T., Alkhorayef, M. & Bradley, D.A., 2018. Tailor-made Ge-doped silica-glass for clinical diagnostic X-ray dosimetry. *Appl. Radiat. Isot*. 138:45-49.

Alyahyawi, A. (2019). Silica-based Passive Dosimeters for sub-Gy Patient-focused Dose Evaluations. PhD thesis. University of Surrey, 2019.

Begum, M., Mizanur Rahman, A.K.M., Abdul-Rashid, H.A., Yusoff, Z., Mat-Sharif, K.A., Zulkifli, M.I., Muhamad-Yasin, S.Z., Ung, N.M., Kadir, A.B.A., Amin, Y.M. & Bradley, D.A., 2015. Comparison of thermoluminescence response of different sized Ge-doped flat fibers as a dosimeter. *Radiat. Phys. Chem.*, 116, 155–159.

Dambuli, K., Mahdiraji, G., Amirkhan, F., Chow, d., Gan, G,K.,Wong, W.R., Hassan, M.A., Tee,D.C., Ismaie, S.A. Ibrahimi, S,a.,.Tamchek,N., and Adikan ,F.M., 2012. Fabrication and Development of Flat Fibers. In Conference: Photonics Global Conference (PGC), 2012, pp. 3–5.

Ghomeishi, M., Mahdiraji, G.A., Adikan, F.R.M., Ung, N.M. & Bradley, D. A., 2015. Sensitive Fibre-Based Thermoluminescence Detectors for High Resolution In-Vivo Dosimetry. *Scientific Reports*, 5, p.13309. Available at: http://www.nature.com/articles/srep13309.

Hashim, S., Bradley, D. a., Peng, N., Ramli, a. T. & Wagiran, H., 2009. The thermoluminescence response of oxygen-doped optical fibres subjected to photon and electron irradiations. *Nuclear Instruments and Methods in Physics Research, Section A*, 619, 291–294.

Hashim, S., Bradley, D.A., Saripan, M.I., Ramli, A.T. & Wagiran, H., 2010. The thermoluminescence response of doped SiO2 optical fibres subjected to fast neutrons. *Appl. Radiat. Isot.*, 68, 700–703.

ICRP, 2012.statement on tissue reactions and early and late effects of radiation in normal tissues and organs--threshold doses for tissue reactions in a radiation protection context. *Annals of the ICRP*, 41, pp.1–322. Available at: http://www.ncbi.nlm.nih.gov/pubmed/22925378.

Issa, F., Abdul Rahman, A.T., Hugtenburg, R.P., Bradley, D.A. & Nisbet, A., 2012. Establishment of Ge-doped optical fibres as thermoluminescence dosimeters for brachytherapy. *Appl. Radiat. Isot.*, 70, 1158–1161.

Lam, S.E., D.A. Bradley, D.A., Khandaker, M.U., 2020. Small-field radiotherapy photon beam output evaluation: detectors reviewed. *Radiat. Phys. Chem.* https://doi.org/10.1016/j.radphyschem.2020.108950

Ma, C. M., 2019. Physics and Dosimetric Principles of SRS and SBRT. *Mathews Journal of Cancer Science*, 4, pp.1–16.

Moradi, F., Ung, N.M., Mahdiraji, G.A., Khandaker, M.U., See, M.H., Taib, N.A. and Bradley, D.A., 2019. Evaluation of Ge-doped silica fibre TLDs for in vivo dosimetry during intraoperative radiotherapy. *Physics in Medicine & Biology*, *64*(8), p.08NT04.

Nawi, S.,Wahib, Zulkepely,N., Amin, Y., Min, U.,Bradley, D.A., Nor, R.B.M. & Maah, M.J., 2015. The thermoluminescence response of ge-doped flat fibers to gamma radiation. *Sensors (Switzerland),* 15, 20557–20569.

Nieder, C., Grosu, A.L. & Gaspar, L.E., 2014. Stereotactic radiosurgery (SRS) for brain metastases : a systematic review. Radiat. Oncol, 9, 151.

O'Beirn, M., Benghiat, H., Meade, S., Heyes, G., Sawlani, V., Kong, A., Hartley, A. and Sanghera, P., 2018. The Expanding Role of Radiosurgery for Brain Metastases. *Medicines*, *5*, 90.

Qian, J., Lin, L., Gonzales, R., Keck, J., Armour, E.P. & Wong, J.W., In Vivo Dosimetry of Stereotactic Radiation Therapy Using Integral Quality Monitor (IQM) System. *Radiation Oncology Biology*, 93(3), p.E614. Available at: http://dx.doi.org/10.1016/j.ijrobp.2015.07.2114.

Palmer, A., Bradley, D.A., Nisbet, A., 2012. Physics-aspects of dose accuracy in high dose rate (HDR) brachytherapy: source dosimetry, treatment planning, equipment performance and in vivo verification techniques. Journal of Contemporary Brachytherapy, 4, 81-91.

Pappas, E., Maris, T.G., Zacharopoulou, F., Papadakis, A., Manolopoulos, S., Green, S. & Wojnecki, C., 2008. Small SRS photon field profile dosimetry performed using a PinPoint air ion chamber, a diamond detector, a novel silicon-diode array (DOSI), and polymer gel dosimetry. Analysis and intercomparison. *Medical Physics*, 35(10), pp.4640–4648.

Ramli, A.T., Bradley, D.A., Hashim, S. & Wagiran, H., 2009. The thermoluminescence response of doped SiO optical fibres subjected to alpha-particle irradiation. *Appl. Radiat. Isot.*, 67, 428–432.

Yaakob, Nor H., Wagiran H., Hossain Md. I., Ramli, A.T., Bradley, D.A. and Hasan Ali, 2011. Low-dose photon irradiation response of Ge and Al-doped SiO_2 optical fibres. Appl. Rad. Isot. 69, 1189-1192.