This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>

Contents lists available at [SciVerse ScienceDirect](http://www.sciencedirect.com)

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

An investigation of the thermoluminescence of Ge-doped SiO₂ optical fibres for application in interface radiation dosimetry

A.T. Abdul Rahman^{a,e,*}, R.P. Hugtenburg^b, Siti Fairus Abdul Sani^a, A.I.M. Alalawi^a, Fatma Issa^{a,f}, R. Thomas^c, M.A. Barry^d, A. Nisbet^{a,d}, D.A. Bradley^{a,g}

^a Centre for Nuclear and Radiation Physics, Department of Physics, University of Surrey, GU2 7XH Guildford, UK

^b Department of Medical Physics and Clinical Engineering, Abertawe Bro Morgannwg UHB and School of Medicine, Swansea University, Swansea SA2 8PP, UK

^c Radiation Dosimetry Team, National Physical Laboratory, Teddington, UK

^d Department of Medical Physics, The Royal Surrey County Hospital (RSCH) NHS Trust, Guildford, GU2 7XX Surrey, UK

^e School of Physics and Material Studies, Faculty of Applied Sciences, Universiti Teknologi MARA Malaysia (UiTM), Campus of Negeri Sembilan, 72000 Kuala Pilah, Malaysia

^f Department of Radiotherapy, Tripoli Medical Centre (TMC), Tripoli, Libya

^g Department of Radiological Sciences, King Saud University, P.O. Box 10219, Riyadh 11432, Kingdom of Saudi Arabia

ARTICLE INFO

Available online 25 November 2011

Keywords:

Radiation synovectomy
Photoelectron dose enhancement
Ge-doped silica fibre
Thermoluminescence dosimetry
MCNPX

ABSTRACT

We investigate the ability of high spatial resolution ($\sim 120 \mu\text{m}$) Ge-doped SiO₂ TL dosimeters to measure photoelectron dose enhancement resulting from the use of a moderate to high-Z target (an iodinated contrast media) irradiated by 90 kVp X-rays. We imagine its application in a novel radiation synovectomy technique, modelled by a phantom containing a reservoir of I₂ molecules at the interface of which the doped silica dosimeters are located. Measurements outside of the iodine photoelectron range are provided for using a stepped-design that allows insertion of the fibres within the phantom. Monte Carlo simulation (MCNPX) is used for verification. At the phantom medium I₂-interface additional photoelectron generation is observed, $\sim 60\%$ above that in the absence of the I₂, simulations providing agreement to within 3%. Percentage depth doses measured away from the iodine contrast medium reservoir are bounded by published PDDs at 80 kVp and 100 kVp.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

Commercial phosphor-based thermoluminescence (TL) dosimeters offer limited spatial resolution of the order of a few mm. Small diameter Ge-doped SiO₂ optical fibres make possible high spatial resolution thermoluminescence (TL) dosimetry $\sim 120 \mu\text{m}$ and provide for an approximate Bragg–Grey cavity, critical for non-tissue equivalent probes. Studies of the dosimetric properties of commercially produced Ge-doped SiO₂ optical fibres have been undertaken by several groups, use being made of synchrotron X-ray microbeam radiation as well as kilovoltage and high energy (megavoltage) photon and electron beams. These demonstrate the potential of Ge-doped SiO₂ optical fibres as a novel form of TL dosimeter for radiation therapy dosimetry (Bradley et al., 2006, 2007; Ramli et al., 2009; Abdul Rahman et al., 2010a, 2010b).

In regard to applications, we address a potential radiotherapy technique and the associated dosimetry in treatment of the

painful joint disease, chronic synovial inflammation. The latter is due to excessive growth of the synovium membrane linking the joints. Normal synovium usually produces synovial fluid that helps lubricate the joint. However, when the synovium swells, it produces an excess of synovial fluid, the latter containing an enzyme that in large quantities eats away at the articular cartilage on the joint surface and eventually leads to damage of the joint surface (Deutsch et al., 1993). Synovectomy, the surgical removal of the inflammation of the synovium membrane of a synovial joint, is one of the treatment options. Radiation synovectomy is an alternative treatment, use of a beta-particle emitting radionuclide being the general method, treating or destroying inflamed and diseased synovium, the beta particles travelling 1–3 mm in soft tissues (Deutsch et al., 1993; Johnson et al., 1995; Clunie and Ell, 1995). As an alternative, X-ray phototherapy is a technique that offers considerable promise (Bradley et al., 2008), also for tumour treatment (Boudou et al., 2007). In such applications, the treatment volume is loaded with a relatively high atomic number medium, for instance iodinated contrast medium (an example of a medium that can safely be used within the body), and exposed to kilovoltage X-rays. At kilovoltage energies the large photoelectric cross sections of iodine, just above the K shell absorption edge, results in

* Corresponding author. Present address: Centre for Nuclear and Radiation Physics, Department of Physics, University of Surrey, GU2 7XH Guildford, UK. Tel.: +441483682722; fax: +441483686781.

E-mail addresses: a.t.abdulrahman@surrey.ac.uk, ahmadtaufek@ns.uitm.edu.my (A.T. Abdul Rahman).

substantial photoelectric interactions. The high linear energy transfer ($11.5 \text{ keV } \mu\text{m}^{-1}$) and short range of the photoelectric interaction products (photoelectrons, characteristic X-rays and Auger electrons) give rise to localised dose enhancement, which promises to be of considerable interest in highly localised tissue treatments, as in the inflamed synovial layer.

Experimental evidence has demonstrated dose enhancement in a gel with added iodine (Boudou et al., 2007), while Monte Carlo calculations have quantified the dose enhancement for various iodine concentrations (Boudou et al., 2007). Present interest is in the potential of Ge-doped SiO_2 optical fibres in measuring photoelectron dose enhancement resulting from the use of such moderate to high-Z media.

2. Materials and methods

2.1. Dosimeter system

The concentration of Ge in doped SiO_2 optical fibres used in this study is 0.15–0.19 mol% based on SEM and EDXRS analysis (Ramli et al., 2009). The effective atomic number, Z_{eff} for Ge-doped SiO_2 optical fibres is 11.4, again determined using SEM and EDXRF analysis (Ramli et al., 2009). This can be compared against the value of Z_{eff} in soft tissue of 7.42 and of Z_{eff} for bones 11.6–13.8 (Jayachandran, 1971). One advantage of Ge-doped SiO_2 optical fibre dosimeters is that they are water resistant and therefore it becomes possible to locate the fibre dosimeter within a particular tissue of interest. Another is that the relatively insubstantial dimensions of the fibres points to their approximating a Bragg–Grey cavity. These factors suggest the possible use of Ge-doped SiO_2 optical fibres in a variety of interface dosimetry situations, as in for instance for dosimetry application in radiation synovectomy.

The dosimetry system herein was based on Ge-doped SiO_2 optical fibres, each with a mean length of $5.0 \pm 0.1 \text{ mm}$ and diameter of $125.0 \pm 0.1 \mu\text{m}$. The Ge-doped silica optical fibres have been selected on the basis of an inter-variation to fixed dose of better than 4% (1 S.D) and linear response for a dose range of 1–50 Gy. The outer cladding of plastic polymer was carefully peeled away from the optical fibre using a fibre stripper. The stripped optical fibres were then cleaned by means of a cotton cloth containing methyl alcohol to minimise the possibility of there being any remnant polymer (Abdul Rahman et al., 2010a, 2010b). By using an optical fibre cleaver (Fujikura, Japan) the optical fibre was divided into lengths of approximately $5.0 \pm 0.1 \text{ mm}$, the practice ensuring a clean cut for each sample. The optical fibres were then placed inside an opaque light-proof gelatine capsule to provide for irradiation, routine storage and handling.

2.2. Phantom device

A model membrane synovial treatment setup has been created using a specially designed phantom made from a polyurethane medium, designated Phantom 1, produced in the form of a cylinder (60 mm diameter $\times$ 60 mm height) and also separately a Perspex cube (70 mm $\times$ 70 mm $\times$ 70 mm), designated Phantom 2, each phantom including a reservoir of iodine (Fig. 1). These variations in phantom design allow for reproducibility studies, the desire being to demonstrate independence of any measured photoelectron dose enhancement from medium or geometry effects. Each setup provided for measurement of dose enhancement resulting from intimate surface contact between the Ge-doped SiO_2 optical fibres and the iodine (I_2) contrast medium. Phantom 1 is a quasi tissue equivalent substance, with mass density of 1.101 g cm^{-3}

and Z_{eff} 8.65 (Adamovics and Maryanski, 2006) while Phantom 2 has a mass density of 1.190 g cm^{-3} and Z_{eff} 6.47 (Qi et al., 2010).

The phantoms have two important design elements. The first is a hole of 10 mm diameter $\times$ 20 mm depth, forming the means for the reservoir containing the iodinated contrast medium. This provides for measurement of photoelectron dose enhancement by arranging intimate surface contact between Ge-doped SiO_2 optical fibres, placed against the walls of the hole proximal to the beam entry surface, and the contrast medium. The arrangement simulates a synovial membrane in contact with the contrast media introduced into the joint space. The contrast media used in this study is iodine NIOPAM (^{270}I) the concentration of which is 370 mg of iodine per ml. The second design element concerns the lower part of the phantom, distant from the iodine reservoir, and formed as a stepped design with 10 mm width for each step. This allows for insertion of the fibres within the phantom to measure the dose deposited in stimulant surrounding soft tissue. Fig. 1 shows the phantom designs; one point of note is the offset reservoir in the polyurethane-based arrangement to further modify the geometries between Phantoms 1 and 2.

2.3. Characterisation of the Ge-doped silica optical fibre

It is recognised that for any communication fibre system, the dopant concentration will vary from point to point along the length of an optical fibre, albeit within a limited range of concentrations. In the absence of a process of radiation sensitivity selection, for a fixed dose of radiation there will result a commensurate range of TL emissions, a situation largely paralleling that for phosphor TL systems. Therefore it is important to select fibre dosimeters of uniform sensitivity to allow for further investigation. This forms an associated selectivity study of dosimeters, incorporating reproducibility and reusability of dosimeters. Selection of Ge-doped SiO_2 optical fibres were performed by irradiating large sample groups at a fixed dose as well as at fixed dose rate. The irradiations were made to provide a dose of 3 Gy at a constant dose rate of 400 cGy min^{-1} ; a field size of $10 \text{ cm} \times 10 \text{ cm}$ was used, from a clinical 6 MV photon beam. The dosimeters were placed in a water phantom at a depth of 2.0 cm using a standard source–surface distance (SSD) of 100 cm. A total of 500 fibres were irradiated. The TL response of irradiated samples was obtained using the TL readout system 12 h post irradiation.

Selection of dosimeters was made in an effort to eliminate outlier data, retaining optical fibres yielding an inter-variation to fixed dose-rate of better than 4% (1 S.D) of the mean value. The optical fibres were then annealed to remove any residual TL signal. The variability of the dosimeter system was then further tested by performing the same irradiation conditions as before.

To investigate the dose response a dose range of 1–35 Gy was delivered at a dose-rate of 222 cGy min^{-1} using a PANTAK Superficial X-ray unit (Pantak Inc., Branford USA). The beam energy used was 90 kVp (HVL=2.5 mm Al) with a field size of 8 cm diameter and surface to source distance (SSD) of 30 cm.

2.4. Dose enhancement in use of iodinated contrast media

Irradiations were made using the PANTAK Superficial X-ray unit described above. Details of the irradiation setup are described in Table 1. The selected fibres were prepared in groups of 20 (to provide information on statistical variation), arranged at each step of the phantom, while for the hole containing a reservoir of iodinated medium, the fibres were located around the aspect of the wall proximal to the incident beam. The iodine contrast medium NIOPAM (^{270}I) 370 (370 mg I/ml) was loaded in

Fig. 1. Photographs (a) and (b) show the side and top view, respectively, of a phantom made from a polyurethane-based medium produced in the form of a cylinder 60 mm diameter $\times$ 60 mm height, while (c) and (d) show the equivalent views of a phantom made from a cube of PMMA (Perspex), lateral dimension 70 mm.

Table 1
Details of irradiation setup for dose enhancement experiments.

	Experiment 1	Experiment 2
Energy (kVp)	90	90
HVL	2.5 mm Al	2.5 mm Al
Dose (Gy)	30	30
Dose rate (cGy min⁻¹)	222	222
Field size	8 cm diameter	8 cm diameter
SSD (cm)	30	30
Phantom	Phantom 1 (polyurethane)	Phantom 2 (Perspex)

the hole of the phantom just prior to the irradiation. Fig. 2 shows the irradiation setup for Phantom 1 and Phantom 2, respectively. Comparison has been made with measurements of dose obtained away from the iodine reservoir as previously described. The fibres, cleansed of all residual iodine, were subsequently readout using a Solaro TL reader (Vinten TLD, Reading, UK).

2.5. Monte Carlo simulation of dose enhancement from iodinated contrast media

Monte-Carlo simulation has been performed to stimulate the dose enhancement resulting from intimate surface contact between Ge-doped SiO₂ optical fibres and the iodine contrast medium. The Monte-Carlo data for this work were generated using MCNPX v.2.6. The spectrum of 90 kVp X-ray use in simulation was handled using the *SpekCalc* programme (Poludniowski et al., 2009). For the simulation, several properties of the beam

Fig. 2. The irradiation setup. The iodine contrast medium NIOPAM (²⁷⁰I) 370 (370 mg I/ml) was loaded into the hole of the phantom just prior to the irradiation. (a) Irradiation of Phantom 1 and (b) irradiation of Phantom 2.

(Table 1), the dosimeter and contrast medium (Table 2), and phantom arrangement (Fig. 2) used in the experiment have been taken into account. The simulation was run for a period of 20 h.

Table 2

The properties of Ge-doped SiO₂ optical fibre and contrast medium used in Monte Carlo simulation.

Ge-doped SiO ₂ optical fibres		Iodine contrast media (NIOPAM 370)	
Density	3.36–2.49 g cm ⁻³	Concentration	76% Lopamidol
Dopant concentration	5–40% mol		0.053 mg Sodium
Diameter	125 μm		370 mg/ml Iodine
Length	10 mm	Specific gravity	1.405

Fig. 3. (a) TL yield distribution from selected Ge-doped SiO₂ optical fibres irradiated at the nominal photon energy of 6 MV for a fixed dose of 3 Gy (delivered at the rate of 400 cGy/min). The red line indicates the mean value. (b) SEM image of Ge-doped silica optical fibres cleaved using an optical fibre cleaver, compared to that cut using a sharp blade.

TL yields were normalised to that resulting from a standard entrance dose to the surface.

3. Results and discussion

3.1. Characterisation of Ge-doped silica optical fibre

Fig. 3a shows the variability in TL yield of Ge doped silica optical fibres following 6 MV photon beam irradiation to a dose of 3 Gy and subsequent selection to only retain fibres with a response ± 1 S.D of the mean value. The selected Ge-doped silica optical fibres are capable of producing a uniform TL response of better than 4% (1 S.D) of the mean value. Fig. 3 also shows SEM images of the cleaved faces of Ge-doped silica optical fibres, (b) resulting from use of a commercial optical fibre cleaver (Fujikura, Japan), while (c) shows results of the use of a sharp blade. It is apparent that irregularities in dopant concentration along the length of the fibre may not be the sole source of TL variation.

3.2. Dose response and energy dependence

The TL responses (Fig. 4) are shown for dose response linearity of different sets of irradiations for different energies from several keV to MeV covering the dose range of 1–50 Gy. Over the range of doses delivered at each energy, linearity of TL yield has been obtained, the correlation coefficient (r^2) being observed to be better than 0.998 (at the 95% confidence level). Over the dose range 1–50 Gy of photon and electron irradiation, least-squares straight line fits to the measured data reveal a TL light yield (in

counts per second per unit mass of fibre, $\times 10^6$) corresponding to a dose-dependency of $\sim 4 \times$ the absorbed dose, measured in Gy, for photon irradiations and $\sim 3 \times$ the absorbed dose, measured in Gy, for electron irradiations. For low energy photon irradiations, results can be compared with that obtained using synchrotron X-ray microbeam radiation therapy facility at the ESRF, delivered at a mean energy of 107 kVp over the energy spectrum 50–350 keV (Abdul Rahman et al., 2010a).

Two particular features are evident from the comparisons of energy response made in Fig. 4. First is the $\sim 20\%$ greater responses obtained in changing from megavoltage to kilovoltage potentials (from the few MV to 90 kVp), being due to the greater probability of photoelectric events in use of the chosen kilovoltage potentials. Second is the observation that optical fibres irradiated at 90 kVp provide a $4 \times$ greater response than those irradiated using a synchrotron X-ray beam of mean energy 107 keV. The latter can be explained in terms of dose-rate non-reciprocity (Schwarzschild) response, described in detail by Abdul Rahman et al. (2010b). In brief, lower dose rates allow ample time for completion of the TL yield process. The PANTAK Superficial X-ray unit delivered dose at a dose rate of 222 cGy min^{-1} , compared to a dose rate delivery of 80 Gy s^{-1} using the synchrotron X-ray microbeam radiation therapy facility at the ESRF. The results also reveal that the fibres provide the basis for sensitive dosimetry throughout the kV to MV range.

3.3. TL yield enhancement in use of iodinated contrast media

Photoelectron dose enhancement evaluation using the two Phantom media previously described were $60 \pm 2\%$ (Phantom 1) and $61 \pm 3\%$ (Phantom 2) as shown in Fig. 5. From MCNP

Fig. 4. TL response of fibres obtained for different beam energies. (a) Photon energy of 6–15 MV and electron energy of 9–20 MeV, (b) 90 kVp tube X-ray and synchrotron X-ray beam of mean energy 107 keV (Abdul Rahman et al., 2010a). The lines are least-squares straight line fits.

simulations, and with TL yields normalised to the TL yield value for a standard entrance dose at 0.5 mm depth, the respective results were $64 \pm 2\%$ and $60 \pm 2\%$ (Fig. 6).

The dose enhancement factor for iodine contrast media has previously been observed for energies near and above the K-edge of iodine (33.2 keV) (Mesa et al., 1999). Using the 90 kVp energy spectrum, the photon energy at which maximum photon yield is obtained is 31.2 keV, photon energies in the range of ~40–50 keV contributing most prominently to the dose enhancement (Edward, 1966). For radiation synovectomy applications, 100 Gy is required to be deposited in the synovial membrane based on the estimation of 1 Gy per 1 g of synovial membrane (Johnson et al., 1995); the enhanced TL yields obtained herein indicate that large dose deposition can be made to happen at an interface between synovium and iodine contrast medium. Photoelectron production and concomitant dose distribution on the few micron scale (Johnson et al., 1995) can be obtained through use of stable iodine in association with incident X-ray irradiation for energies above and close to the absorption edge, the K-edge in this case. This may suggest that radiation synovectomy using a beta emitting radionuclide such as, ^{125}I , with a risk of skin necrosis and of organ damage due to leakage of activity from the joint capsule, could be replaced by the present so-called combination radiotherapy technique. This may lead to minimisation of dose to

Fig. 5. TL yield enhancement for fibres in intimate contact with iodine contrast medium. (a) Experiment 1 using polyurethane medium and (b) experiment 2 using PMMA medium.

healthy tissue and delivery of a well prescribed dose to the target, in this case the synovial membrane.

4. Conclusions

Studies of Ge-doped SiO_2 optical fibres for applications in interface radiation dosimetry have been carried out. The potential of the dosimeters have been examined in regard to measurement of dose enhancement from iodinated contrast medium. In the present study, commercially available Ge-doped silica optical fibres have been shown to possess a number of desirable TL characteristics, in terms of dose stability, linearity of response, and sensitivity to dose. At fixed dose-rate, the dosimeters were found to produce a flat response of better than 4% (1 S.D) of mean TL distribution and showed good linearity ($r^2 = 0.998$) of response up to a dose of 50 Gy for photon and electron beams. Over the dose range of 1–35 Gy, investigated at 90 kVp using a superficial X-ray treatment unit, linearity is obtained ($r^2 > 0.998$). Photoelectron dose enhancement measured in polyurethane and Perspex shows TL yields some ~60% greater than that obtained in the absence of the iodinated medium. This has been modelled using Monte Carlo simulation (MCNPX v.2.6). The measured percentage depth dose (PDD) using polyurethane and Perspex media agree with each other to within 2% and are bounded by the published PDD curves for 100 kVp and 80 kVp spectra as reported in BJR Supplement No 25 for water (Joint Working Party of BIR and IPEM, 1996).

Fig. 6. Monte Carlo simulation of TL yield enhancement for fibres in intimate contact with iodine contrast medium. (a) MCNPX simulation for polyurethane medium and (b) MCNPX simulation for PMMA.

Acknowledgement

The authors would like to thank members of the Royal Surrey County Hospital (RSCH), Department of Medical Physics, for help in performing the irradiations, to Dr. Suhairul Hashim and the University of Technology Malaysia (UTM) for SEM analysis; the

University of Technology MARA Malaysia (UiTM) and the Ministry of Higher Education of Malaysia (MOHE) for supporting a research studentship.

References

- Abdul Rahman, A.T., Bradley, D.A., Doran, S.J., Thierry, B., Bräuer-Krisch, E., Bravin, A., 2010a. The thermoluminescence response of Ge-doped silica fibres for synchrotron microbeam radiation therapy dosimetry. *Nucl. Instrum. Methods Phys. Res. A* 619, 167–170.
- Abdul Rahman, A.T., Nisbet, A., Bradley, D.A., 2010b. Dose-rate and the reciprocity law: TL response of Ge-doped SiO₂ optical fibers at therapeutic radiation doses. *Nucl. Instrum. Methods Phys. Res. A* 652, 891–895.
- Adamovics, J., Maryanski, M.J., 2006. Characterisation of presagtm: a new 3-D radiochromic solid polymer dosimeter for ionising radiation. *Radiat. Prot. Dosimetry* 120, 107–112.
- Boudou, C.T., Rousseau, S.I., Lamalle, J., Adam, L., Est, J.F., Ve, F., Elleaume, H., 2007. Polymer gel dosimetry for synchrotron stereotactic radiotherapy and iodine dose-enhancement measurements. *Phys. Med. Biol.* 52, 4881–4892.
- Bradley, D.A., Hugtenburg, R.P., Hashim, S., Okoya, O.O., Ramli, A.T., Wagiran, H., 2006. The development of doped radiosensitive glass solid state science and technology. In: *The Second International Conference on Solid State Science and Technology 2006; ICSST 2006 Malaysia. Proceedings of the American Institute of Physics Conference*, vol. 909, pp. 9–18.
- Bradley, D.A., Hugtenburg, R.P., Hashim, S., Okoya, O.O., Yusoff, A.L., Hassan, A.A.M., Ramli, A.T., Wagiran, H., 2007. The development of doped radiosensitive glass. In: *AIP Conference Proceedings*, vol. 909, pp. 9–18.
- Bradley, D.A., Hugtenburg, R.P., Daar, Eman, Pierce, N., Nisbet, A., Manolopoulos, S., 2008. Scanned synchrotron microbeam X-ray radiation synovectomy using an iodine converter. *New Prospects for Brain Tumour Radiotherapy: Synchrotron Light and Microbeam Radiation Therapy*. Esrf, Grenoble.
- Clunie, G., Ell, P.J., 1995. A survey of radiation synovectomy in Europe, 1991–1993. *Eur. J. Nucl. Med. Mol. Imaging* 22, 970–976.
- Deutsch, E., Brodack, J., Deutsch, K., 1993. Radiation synovectomy revisited. *Eur. J. Nucl. Med. Mol. Imaging* 20, 1113–1127.
- Edward, R.E.A.H.W., 1966. Experimental study Of the photon energy spectrum of primary diagnostic X-rays. *Phys. Med. Biol.* 11, 225.
- Jayachandran, C.A., 1971. Calculated effective atomic number and kerma values for tissue-equivalent and dosimetry materials. *Phys. Med. Biol.* 16, 617.
- Johnson, L.S., Yanch, J.C., Shortkroff, S., Barnes, C.L., Spitzere, A.I., Sledge, C.B., 1995. Beta-particle dosimetry in radiation synovectomy. *Eur. J. Nucl. Med. Mol. Imaging* 22, 977–988.
- Joint Working Party of BIR and IPEM 1996. Central axis depth dose data for use in radiotherapy. In: *British Journal Of Radiology Supplement* 25. British Institute Of Radiology, London.
- Mesa, A.V., et al., 1999. Dose Distributions Using Kilovoltage X-Rays and Dose Enhancement From Iodine Contrast Agents.
- Poludniowski, G., et al., 2009. Spekcalc: a program to calculate photon spectra from tungsten anode X-ray tubes. *Phys. Med. Biol.* 54, N433.
- Qi, Z., et al., 2010. Quantitative imaging of electron density and effective atomic number using phase contrast Ct. *Phys. Med. Biol.* 55, 2669.
- Ramli, A.T., Bradley, D.A., Hashim, S., Wagiran, H., 2009. The thermoluminescence response of doped SiO₂ optical fibres subjected to alpha-particle irradiation. *Appl. Radiat. Isot.* 67, 428–432.