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Dosimetry audits and intercomparisons in radiotherapy: A Malaysian profile

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A R T I C L E I N F O

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A B S T R A C T

Quality audits and intercomparisons are important in ensuring control of processes in any system of endeavour. Present interest is in control of dosimetry in teletherapy, there being a need to assess the extent to which there is consistent radiation dose delivery to the patient. In this study we review significant factors that impact upon radiotherapy dosimetry, focusing upon the example situation of radiotherapy delivery in Malaysia, examining existing literature in support of such efforts. A number of recommendations are made to provide for increased quality assurance and control. In addition to this study, the first level of intercomparison audit i.e. measuring beam output under reference conditions at eight selected Malaysian radiotherapy centres is checked; use being made of 9 µm core diameter Ge-doped silica fibres (Ge-9 µm). The results of Malaysian Secondary Standard Dosimetry Laboratory (SSDL) participation in the IAEA/WHO TLD postal dose audit services during the period between 2011 and 2015 will also been discussed. In conclusion, following review of the development of dosimetry audits and the conduct of one such exercise in Malaysia, it is apparent that regular periodic radiotherapy audits and intercomparison programmes should be strongly supported and implemented worldwide. The programmes to-date demonstrate these to be a good indicator of errors and of consistency between centres. A total of ei + ght beams have been checked in eight Malaysian radiotherapy centres. One out of the eight beams checked produced an unacceptable deviation; this was found to be due to unfamiliarity with the irradiation procedures. Prior to a repeat measurement, the mean ratio of measured to quoted dose was found to be 0.99 with standard deviation of 3%. Subsequent to the repeat measurement, the mean distribution was 1.00, and the standard deviation was 1.3%.

1. Introduction

The medical use of radiation and the supporting dosimetry are well understood processes, controlled in accord with established international practices and tolerances. Protocols supporting these continue to evolve in line with the notion of continuing quality improvement. Present interest concerns therapeutic applications and in particular, the accuracy and precision of delivery of the elevated doses that support curative and palliative scenarios, towards promoting quality of life of the sufferer. Discrepancies from prescribed doses have potential subtle, severe or even lethal consequences, depending on the magnitude of discrepancies. In regard to manifest discrepancies, one draws attention to a number of well-publicised radiotherapy incidents, catalogued and analysed by the (International Atomic Energy Agency (2000). Not least among the considerable efforts that have been devoted in national and international contexts towards minimising errors and uncertainties in dose delivery is the dosimetric audit and intercomparison exercise. As part of the quality assurance (QA) process, to ensure continuing improvement in the quality in radiation treatment (Nisbet et al., 1998; Thwaites et al., 1992), the dosimetric audit has an important role in ensuring optimised clinical outcomes. In this respect, in order to achieve consistency and accuracy in delivery of absorbed dose to a target volume in radiotherapy dosimetry, the ICRU (International Commission on Radiation Units and Measurements) issued Report 24, calling for dose delivery to within at least ± 5% of the prescribed dose (ICRU, 1976). Other more recent reviews have recommended stricter

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limits on dose delivery, as for instance, ± 3.5% (Mijnheer et al., 1987) and ± 3% (Brahme, 1984). Here, the dosimetry audit and intercomparison exercises have been introduced as part of the effort towards conforming to such recommendations, seeking to detect errors, inexact implementation or misinterpretation of recommendations, equipment issues or mistakes (Nisbet and Thwaites, 1997).

2. Legislative framework in Malaysia

The Atomic Energy Licensing Act 1984 (Act 304) is the primary instrument in controlling the use of ionising radiation in industrial and medical sectors in Malaysia. The Act is supported by its subsidiary regulations which provide safety standards for radiation practices, guidelines for licensing and enforcement activities and transport requirements for radioactive materials and waste. Some of these regulations are currently under review, with new regulations yet to be approved. The Act replaced the previous Radioactive Substances Act 1968, in April 1984, due to the rapid growth of atomic energy activities in Malaysia. The Act has a clause for the formation of the Atomic Energy Licensing Board (AELB) to operate as the highest authority in order to enforce the requirements act and its subsidiary regulations (Mohd Ali, 2004). It also has a clause identifying the Director General of Health Malaysia as the authority enforcing requirements of the Act and its subsidiary regulations for medical activities. In addition to the Act and its regulations, the legal framework is also supported by other legally binding circulars, standards, and guidelines together with non-legally binding local rules and instruction manuals (Fig. 1).

In order to ensure that the existing Act and regulations continue to be appropriate for current technology without neglect of the social and economic factors in Malaysia, the AELB with the help of the International Atomic Energy Agency (IAEA) has initiated a process of revision. Progress of the revision exercise process has been slow for a number of reasons, the current status of the revision and the recommendations of the IAEA being discussed by Mohd Yus of (Mohd Ali, 2004). In parallel, with the help of several international bodies, the Ministry of Health Malaysia (MOH) is developing more specific and comprehensive regulations concerning control of the use of ionising radiation in the medical sector.

3. Development of dosimetry audits in Malaysia

The Atomic Energy Licensing Board (AELB) and the Ministry of Health Malaysia (MOH), the principal authorities for ensuring radiation safety within the country, have played an important role in dosimetry audit development in Malaysia. Together with other agencies such as the Malaysian Nuclear Agency (MNA) (http://www.nuclearmalaysia.gov.my/), the Malaysian Association of Medical Physics (MAMP) (http://www.mamp.org.com), the Associate of Private Hospitals (APHM) (www.hospitals-malaysia.org) and the Malaysian Radiation Protection Association (MARPA) (http://www.marpa.org.my/marpa/), national research, and development (R & D) efforts are now well established. As a member state, Malaysia also receives assistance from the IAEA in the form of expert visits and financial support (Daud,1996).

The Malaysian Secondary Standard Dosimetry Laboratory (SSDL), established within the MNA is recognized by the Malaysian accreditation body as a national calibration laboratory for radiation protection and radiotherapy purposes. This laboratory is for instance responsible for providing personal dosimeters to all users in Malaysia, having now done so for in excess of 18 years (Mohd Ali, 2004); it also ensures that all instruments used in radiation at therapy, protection and environmental levels are calibrated. For present interest this includes radiation survey meters and therapy dosimeters (ion chambers), calibrated following the relevant IAEA Codes of Practices, as provided for by the IAEA as a Primary Standard Dosimetry Laboratory (PSDL) (Kadni, 2005).

In medical radiation practices, currently, in Malaysia there are 54 linear accelerators, 2 cobalt-60 teletherapy machines, 15 brachytherapy units, 11 simulators and 4 computerised tomography units, operating in 27 radiotherapy and oncology centres (Samat et al., 2009a; Lim, 2006). In order to ensure these facilities produce consistent and accurate absorbed dose delivery, audits and intercomparison exercises are being carried out, predominantly by the MNA SSDL, with cooperation from the Ministry of Health Malaysia (MOH).

4. Review of participations of audit and intercomparison programmes

Most prominent among the audit and intercomparison programmes

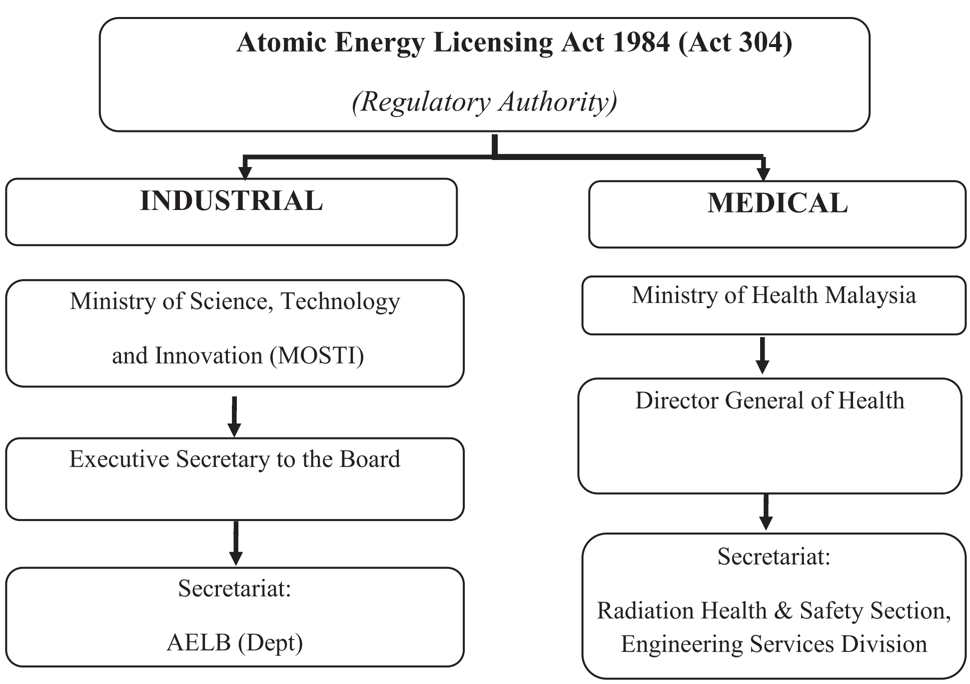

Fig. 1. Organisational arrangements for control of sources of ionising radiations in Malaysia.

have been those for megavoltage photon beams, being a programme organized by the IAEA/WHO (www.hospitals-malaysia.org) in collaboration with the SSDL. Thirty seven such exercises have been carried out over the period 1985–2008. Other programmes in which the SSDL have similar involvement are: kilovoltage photon beams (Ng et al., 1998) (carried out from 1993 to 1995), electron beams (Mohd Ali et al., 1995), dose equivalent H_P (10) in mixed n-γ fields (Mohd Ali, 2004) and deep dose (H_P (10)) and skin dose (H_P (0.07) assessments.

SSDL also has participated in the two key comparison projects of: (i) measurement of air kerma for medium-energy x-rays (100 kV to 250 kV) between 2000 and 2003 (Lee et al., 2008); and (ii) comparison of absorbed dose to water for ^{60}Co between 2009 and 2010 (Chun et al., 2013) performed by APMP (Asia Pacific Metrology Programme) Dosimetry Working Group. From a bilateral comparison with BIPM, the measured value of the Nuclear Malaysia and BIPM calibration coefficient agreed within 1.2% at each of the four x-ray beam qualities and 0.22% for absorbed dose to water using ^{60}Co.

Other than IAEA involved evaluations, there has also been an intercomparison study by Rassiah et al. (2004), organized as a collaboration between the University of Malaya Medical Centre (UMMC) and the University of Wisconsin, Radiation Calibration Laboratory (UWRCL). In general, three types of dosimeters have been used in these intercomparisons: ionisation chambers (Samat et al., 2000), Lithium fluoride thermo luminescence dosimeters (TLD's) (Samat et al., 2009a) and alanine (Mohd Ali, 2004). To-date, ^{60}Co, 6 MV, 10 MV, 15 MV and 18 MV energies have been checked by the IAEA for beam calibrations (Samat et al., 2009a).

According to Samat et al. (2009a), the result for TLDs and ion chamber comparisons during the years of 1985–2008 (given as percentage deviations between SSDL Malaysian stated doses and IAEA mean dose), showing that the discrepancies are well within the IAEA limit of ± 3.5%. Conversely, results of the TLD studies carried out by Rassiah et al. (2004) and Lee et al. (2008) and supported by Abdullah et al. (2016) showed there to be a few radiotherapy centres yielding deviations of greater than ± 5%, being traced to errors in irradiation set-up such as incorrect field size or Source to Surface Distance (SSD), mistake in absorbed dose calculation and sometimes to lack of physics support at ^{60}Co beam facilities.

In 2000, SSDL also use alanine dosimeters for IAEA intercomparison, to check on its gamma calibration facilities and the deviations were found to be within the acceptable limit set by IAEA i.e. ± 5% (Mohd Ali, 2004).

5. Benefits of Malaysian national dosimetry audits and problems reported

Currently, there are no known published reports concerning radiotherapy incidents in developing countries in Asia or Africa (World Health Organization, WHO, 2008). In addition, the paucity of data regarding quality control of delivery of dose in such regions leads to no real understanding of the extent to which quality is maintained, although it is clear that this is highly variable. The only published studies have concerned evaluation of dosimetry practices in a number of developing countries, focusing on measurements carried out by Izewska et al. (2006); Izewska and Andreo (2003). In regard to Malaysia, the intercomparison programme has increased confidence in the accuracy and consistency of dose delivery in radiation therapy (Rassiah et al., 2004; Samat et al., 2009b). Furthermore, an external audit of an oncology practices enables identification of 'areas of need' in terms of gaps in knowledge and skills of the staff involved (Shafiq et al., 2009).

Thus said, there remains a number of unsolved problems in seeking to implement a comprehensive audit intercomparison programme in Malaysia, including a lack of experienced medical physicists (Rassiah et al., 2004) and high workloads for the radiation oncology staff (Ng et al., 1998; Shakespeare et al., 2006).

6. Recommendations

A number of recommendations have been offered in addressing the problems stated above. These are:

(i) While Samat et al., (2009a) noted results from a Malaysian postal audit at radiotherapy level 1 (postal audits for photon beams in reference condition), it would seem necessary to extend future auditing activities at level 2 by using more complex methodologies, as proposed by the IAEA (e.g. non-reference condition) (Lim, 2006; Iżewska et al., 2007);

(ii) Device checks should be made towards the end of the dosimetry chain (Thwaites et al., 2002) (where the doses within a standard phantom for a planned treatment are measured, covering checks of basic dosimetry, patient data acquisition, treatment planning and delivery);

(iii) Strengthening of radiotherapy infrastructures to improve the audit outcomes to make this comparable with that of developed countries and to enhance the training of medical radiation physics staff and suitable dosimetry facilities (Shafiq et al., 2009; Martenka et al., 2008);

(iv) A good networking between the Malaysia government, private sectors, and non-government organisations are needed in order to improvement of treatment facilities and to be able to have knowledge transfer between the centres similar with the UK's audit networking systems (Thwaites et al., 2002);

(v) In vivo dosimetry should be promoted (Thwaites et al., 2002);

(vi) Independent dosimetry checks in co-operation with peers should be encouraged (The Proceedings to The IAEA Meeting On Standards and Codes of Practice in Medical Radiation Dosimetry, 2002);

(vii) Follow the audit systems such as the UK's which include the use of intercomparisons themselves, implementation of Quality Systems and regular Quality audit via Regional Dosimetry audit network (Clark et al., 2015);

(viii) To achieve high accuracy of delivery dose to radiotherapy patient, quality assurance programmes consist of radiotherapy facilities, dosimetry and process should be supported, strengthened, and promoted;

(ix) Clinical audit should be included in the dosimetry checklist in order to fulfil assured clinical practice (Martenka et al., 2008);

(x) In order to increase the number of dosimetry audit expertise and well trained medical physicists in complex radiotherapy techniques, special clinical training courses such as IMRT/IGRT and dosimetry audit should be organized frequently by authority department. In the course, experts in radiotherapy dosimetry from IAEA, EQUAL and RPC should be invited;

(xi) Lack of medical physics staffs can be solved when Malaysian government especially Public Service Department of Malaysia, Ministry of Health and universities work together to promote the profession of medical physics to university students such as providing a scholarship and opportunity to have industrial training (hands-on) in government and private hospitals, and SSDL Malaysia Nuclear Agency (The Proceedings to The IAEA Meeting On Standards and Codes of Practice in Medical Radiation Dosimetry, 2002);

(xii) Consider the development of advanced dosimetry audits to assure the accuracy of complex radiotherapy treatments (Hussein et al., 2014);

(xiii) Development of mailed anthropomorphic phantom or more tissue equivalent, 3 dimensional relative and absolute dosimetry for clinical trial and advanced techniques audit programmes should be encouraged and promoted.

Table 1
Results of TLD measurements for Co-60 and high energy photons in the IAEA/WHO TLD Postal Dose Quality Audit for Malaysian SSDL.

Radiation quality	Year of participation	SSDL stated dose (Gy)	IAEA mean dose (Gy)	Δ (%)[a]	Ratio[b]
1.25 MeV ^{60}Co	2009	2.05	2.05	−0.2	1.00
	2010	2.06	2.12	−2.5	1.03
	2014	2.00	2.01	−0.4	1.00
6 MV X-rays	2011	2.02	2.01	0.6	0.99
	2013	2.01	2.02	−0.4	1.00
	2016	2.00	2.00	0.0	1.00
10 MV X-rays	2012	2.02	2.02	0.0	1.00
	2015	2.03	2.05	−1.2	1.01

[a] Percentage deviation relative to IAEA measured dose = 100x (User stated dose – IAEA mean dose)/IAEA mean dose.
[b] Ratio = IAEA mean dose/User stated dose.

7. A Malaysian SSDL participation in the IAEA/WHO TLD postal dose quality audit service during years of 2011–2015

During the years of 2009–2015, a total of 8 intercomparison exercises were carried out by Malaysian SSDL in the IAEA/WHO TLD Postal Dose Quality Audit Service. Results of the calculated percentage deviations between the SSDL and the IAEA results for TLD measurements with both ^{60}Co (1.25 MeV) and Linac (6 MV and 10 MV photon beams) are shown in Table 1. As expected, all of them yield deviations within the IAEA limit of +3.5%. The mean of the distribution is −0.50% and the standard deviation is 0.95%. The deviations vary between a minimum percentage relative deviation of −2.5% and a maximum of 0.6%.

8. Assessment of current dosimetry consistency in participating Malaysian radiotherapy centres and development of a mailed Ge-doped optical fibres dosimetry audit

The aim of the present investigation, using high energy photon beams, is to undertake a pilot study aimed at establishing the potential of a mailed commercial Ge-doped optical fibre TL-system in measuring beam output under reference conditions and assess the current achieved consistency in dosimetry in participating Malaysian radiotherapy centres. The silica-glass optical fibre used is single-mode INOCORP (Canada) Ge-doped optical fibre, core diameter 9 µm and cladding diameter 116 ± 0.1 µm. The preliminary Ge-doped optical fibre irradiations were performed using a Varian linear accelerator located at Royal Surrey Country Hospital (RSCH) (Noor et al., 2014). The audit was carried out for eight Malaysian radiotherapy centres located at seven locations throughout the country, covering Peninsular Malaysia and one location in Malaysian Borneo, with a total of eight beam calibrations being checked. Three of the participating centres were from general hospitals, while the other five were private medical centres. The most commonly used dosimetry protocol in Malaysia to determine absorbed dose to water is the IAEA TRS 398 (International Atomic Energy Agency, 2000). Seven out of the eight participating radiotherapy centres in this audit study have already participated in LiF TLD postal dose audit programmes organized by various international agencies such as the IAEA, ESTRO and the Forum for Nuclear Cooperation in Asia (FNCA) Radiation Oncology project. Capsules were mailed to these centres for irradiation to an absorbed dose to water of 2 Gy at 10 cm depth under reference conditions. To ensure a standardized irradiation procedure, four Ge-doped optical fibre capsules, a Ge-doped optical fibre holder (Fig. 2a and b), a radiotherapy centre specific details sheet, a technical instruction sheet and a dose data report sheet were sent to each radiotherapy centre. In the described methodology

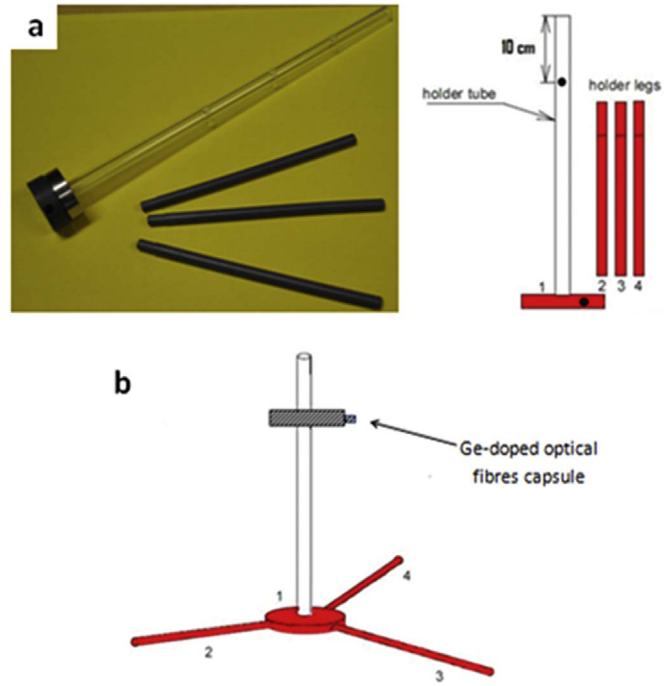

Fig. 2. a) Ge-doped optical fibres holder and constituent support parts; b) Schematic of assemble holder with the Ge-doped fibres capsule for Ge-doped irradiation.

three of the Ge-doped fibre capsules were requested to be irradiated while the fourth capsule was asked to be treated as the control capsule, used to record environmental influences during transportation and storage. Using the returned fibres, TL results were analysed according to practices described by the International Atomic Energy Agency (2000) and from this, a report of the variation from the standard 2 Gy dose was constructed for each of the participant centres.

8.1. Reporting the audit results

According to (ISO, 1992) the percentage relative deviation between the obtained and quoted dose is defined as:

$$\Delta D \;=\; 100\% \,\frac{D_{participating} - D_{fibres}}{D_{fibres}} \tag{1}$$

where absorbed dose equation (D_{fibres} and $D_{participating}$) were developed by Noor et al. (2014) was employed. In this study, an acceptance limit of ± 5% ($0.95 \le \left(\frac{D_{fibres}}{D_{participant}}\right) \ge 1.05$) has been set for this deviation, as previously used by the ESTRO quality assurance network (EQUAL) and the IAEA TLD postal programme. Deviation of more than ± 5% and less than ± 10% ($0.90 \le \left(\frac{D_{fibres}}{D_{participant}}\right) \ge 0.95$) **or** ($1.05 \le \left(\frac{D_{fibres}}{D_{participant}}\right) \ge 1.10$) are considered minor and deviations exceeding ± 10% ($\left(\frac{D_{fibres}}{D_{participant}}\right) \le 0.90$ **or** $\left(\frac{D_{fibres}}{D_{participant}}\right) \ge 1.10$) are regarded as major (International Atomic Energy Agency, 2000).

Full details of the audit results are mailed to participating centres if the deviation is within the acceptance limit. However, if there is a deviation outside tolerance, the participating centre is informed that there has been a deviation but are not informed of its magnitude or deviation and will be asked to repeat the measurement again as soon as possible. In the case of a major deviation following the repeat measurement, the Malaysian SSDL is informed and a detailed on-site audit visit carried out by SSDL Malaysia may then be required.

8.1.1. Uncertainty of deviation in the ratio $\left(\frac{D_{fibres}}{D_{participant}}\right)$

Generally all the audit results are reported as the ratio of the obtained dose as calibrated at reference centres, D_{fibres}, to the dose quoted by the participating centres, $D_{participant}$. To calculate the uncertainty in this ratio, the following equation was applied:

$$u\left(\frac{D_{fibres}}{D_{participant}}\right) = \sqrt{\frac{u_c(D_{fibres})^2 + u(D_{participant})^2}{I}} \quad (2)$$

where $u_c(D_{fibres})$ is the uncertainty in the dose obtained from the fibre measurement published by Noor et al. (2014), $u(D_{participant})$ is the uncertainty in the dose quoted by the participating centres according to the IAEA Code of Practice TRS 398 (International Atomic Energy Agency, 2000). The number of fibres used to determine the ratio is represented by *I*.

8.2. Malaysian mailed Ge-doped optical fibres postal dose audit results

Of the centres participating in previous audits, all the results were found to produce values in the range less than ± 3%, noting the acceptance limit to be ± 5%. The present postal dose audit, based on the use of Ge-doped optical fibre, is the first of its kind to be carried out. The results of the audit are shown in Fig. 3a. Each data point corresponds to the average from three capsules of Ge-doped fibre. The histogram corresponds to ratios of the obtained dose calculated ($D_{(fibres)}$) relative to the dose quoted by each of the Malaysian radiotherapy centres ($D_{(participant)}$). The mean ratio of measured to quoted dose was 0.99 with a standard deviation of 3%. The ratio of the results varies between a minimum dose of 0.92 and a maximum of 1.03. One out of the eight beams checked was shown to produce a deviation of more than ± 5% but less than ± 10%. The particular centre has never previously participated in any audit programme involving mailed TLDs. Investigation showed that as a result of misinterpretation of the instructions on how to carry out the irradiation, the Ge-doped fibres were subjected to an incorrect dose. The particular centre was informed about the issue and asked to perform a second measurement. Fig. 3b shows the distribution of results following the repeat measurement. The mean distribution was 1.00 with a standard deviation of 1.3%. The maximum and minimum result of the ratio is 1.03 and 0.99 respectively, all within the acceptance limit (± 5%). Izewska and Andreo (2000) stated that “only 65% of the hospitals that received TLD for the first time produced results within the acceptance limit (± 5%), while 81% of the institutions participating regularly in the audits have produced results within the (± 5%) limits”. Of importance is that such efforts, viz regular (periodic) participation in external audits, can help to maintain accurate dosimetry, and especially so in developing countries where such support can be invaluable (Rassiah et al., 2004).

8.2.1. Uncertainty in the ratio of $\left(\frac{D_{fibres}}{D_{participant}}\right)$

Uncertainty in the ratio of $\left(\frac{D_{fibres}}{D_{participant}}\right)$ has been calculated in accord with Eq. (2). All ion chambers used in Malaysia are calibrated at the Malaysian SSDL; the Malaysian SSDL factors are traceable to the IAEA and sequentially traceable to the Bureau International des Poids et Measures (BIPM). The uncertainty attributed to the SSDL is 1.2% at a 95% confidence (two standard deviation) determined by the International Atomic Energy Agency (2000). Using $u(D_{participant})$ as 1.20% and $u_c(D_{fibres})$ as 2.11, $u\left(\frac{D_{fibres}}{D_{participant}}\right)$ provides an uncertainty of 1.40%.

9. Conclusion

The audit carried out to-date indicates that one out of eight centres has shown a minor deviation. Unfamiliarity of the physicist of the particular centre with the irradiation procedures was found to be a possible cause of the deviation. The mean ratio of measured to quoted dose was found to be 0.99 with standard deviation 3%, prior to repeated measurement. Following repeated measurement of the audit, the mean distribution was found to be 1.00 with standard deviation 1.3%. Using Eq. (2), uncertainty in the ratio of dose measured by fibres to the dose stated by the participants is found to be 1.4%. In conclusion, with repeat intercomparison programmes, the deviations have also been shown to decrease as has improved consistency of dosimetry. 9 µm

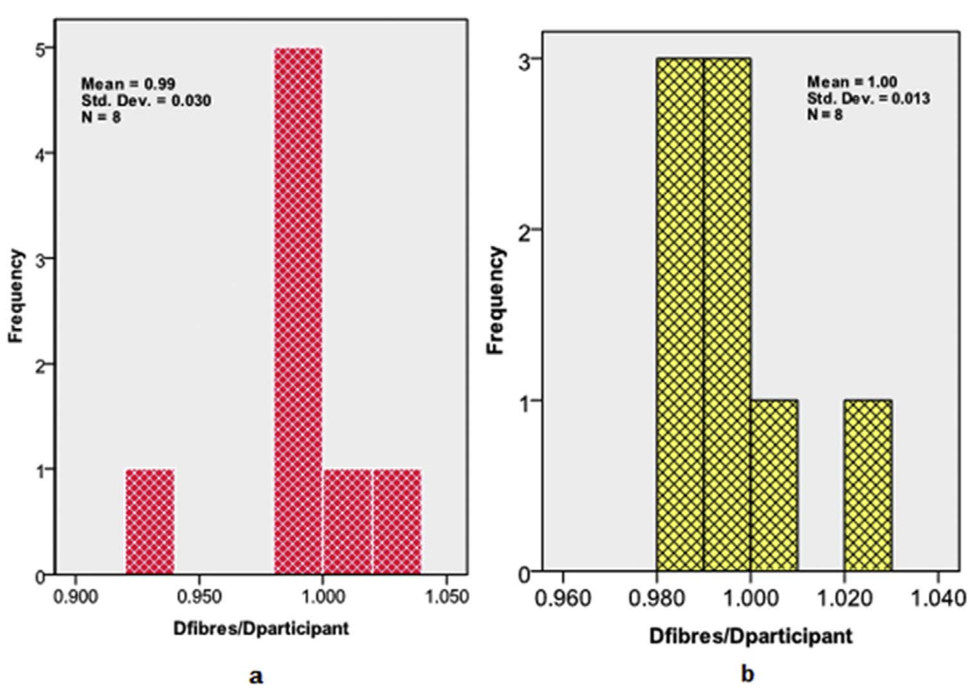

Fig. 3. a Histogram of the relative TL responses ($D_{(fibres)}/D_{(participant)}$) of the eight participating Malaysian radiotherapy centres. The distribution of the mean is 0.99 with 0.03 standard deviation. Distribution of the mean is 0.99 with 0.03 standard deviation. Fig. 3b Histogram of the relative TL responses ($D_{(fibres)}/D_{(participant)}$) of the eight radiotherapy centres following one repeat irradiation. Note that $D_{(fibres)}$ is the dose obtained at the RSCH relative to the dose quoted by the Malaysian radiotherapy centres, $D_{(participant)}$). The distribution of the mean is 1.00 with 0.01 standard deviation.

diameter core Ge-doped fibres represent a viable system for use in mailed audit radiotherapy programmes.

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