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Original Article

Systematic in vivo dosimetry for quality assurance using diodes 2: Assessing radiotherapy techniques and developing an appropriate action protocol

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Abstract

Purpose: Having previously reviewed the implementation of systematic in vivo dosimetry at the Norfolk and Norwich Hospital this paper examines the results of entrance dose measurements for specific sites/techniques and determines whether different action/alert protocols are required for these different categories.
Methods and materials: Entrance dose measurements using p-type diodes were analysed for the following treatment categories: Breast, head and neck in beam direction shell, abdomino-pelvic and intrathoracic. A 4% tolerance was applied.
Results: Mean deviations from expected dose and proportion of measurements exceeding tolerance were: Breast: $+1.15\% \pm 3.04\%$ (1SD), $238/1073 \geq 4\%$; Head and neck: $+0.35\% \pm 2.20\%$ (1SD), $21/326 \geq 4\%$; Abdomino-pelvic: $+0.52\% \pm 2.75\%$ (1SD), $93/712 \geq 4\%$; Intrathoracic: $-0.01\% \pm 2.75\%$ (1SD), $22/119 \geq 4\%$. Significant improvements in results for breast patients were noted following the introduction of a commercial breast board. The results for abdomino-pelvic patients confirmed a substantial variation in diode response under short FSD, wedged fields at 16 MV (that had not been corrected for). The statistical uncertainty in dose measurement for each treatment category was calculated in order to assist determination of appropriate tolerance levels.
Conclusions: A blanket tolerance of 4% was generally too low given the extent of measurement uncertainty. The relatively high number of readings outside tolerance where identification of errors was difficult/impossible resulted in inconsistent application of the action protocol. Some widening of tolerances is likely to improve quality of procedure and treatment. Appropriate action levels are recommended for each treatment category.

Keywords

In vivo dosimetry; diodes; quality assurance

INTRODUCTION

In vivo dosimetry (IVD) has been demonstrated to be a valuable method for verifying dose delivery and can identify systematic and random errors that may occur during the various stages of planning and treatment delivery.[1] The physical characteristics of commercial diodes for use in IVD have been examined by several authors[2–11] and it is well established, that with careful use, high precision can be achieved. A number of centres have reported their experiences of IVD on cohorts of patients.[12–24]

Our previous paper[12] described our experiences of implementing systematic IVD using entrance diode dosimetry at the Norfolk and

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Norwich Hospital and reviewed the results of 2254 measurements on 661 patients receiving MV photon therapy over a 17 month period. The purpose of this subsequent work is to:

- Examine the results of IVD for specific sites/techniques in more detail as the accuracy of dose delivery and dose measurement clearly depends on certain characteristic features of radiation technique, treatment site and irradiation conditions.
- Determine whether different action/alert protocols are required for different categories of treatment site/technique – a concept tentatively suggested by some authors.[22,24]

Defining appropriate tolerance levels and associated action protocols is of crucial importance if IVD is to successfully contribute to a departmental QA programme and their determination will depend on a number of factors. Perhaps the most important of these is the level of accuracy considered clinically significant and so it is not surprising that many action levels are justified on the basis of recommendations related to the accuracy achievable in practice.[25–27] However, basing tolerance purely on suggested levels of accuracy can result in ineffective and inefficient IVD if there are inherent, large uncertainties in dose measurement through, say, inadequate correction for variations in diode response. This would result in many large deviations being detected where differentiating between true errors in dose delivery and errors related to dose measurement becomes problematic and considerable time and effort will be devoted to (often) fruitlessly investigating deviations. Such a practical consequence is an important consideration for most departments.

Wolff et al.[21] reported that without any corrections other than accounting for sensitivity drop, their *n*-type diodes exhibited a maximum uncertainty of 6.4%. As this was greater than the 5% tolerance level applied it suggests that sources of deviations may have been uncertain. It is therefore important to carefully consider the level of uncertainty related to diode measurement *in practice* in defining an appropriate tolerance level that minimises the chance of missing clinically significant deviations whilst also minimising the likelihood of clinically unimportant deviations that reflect acceptable random variations.

METHOD AND MATERIALS

As previously described,[12] entrance dose measurements were performed on all new planned patients receiving MV photon treatment on the department's three linear accelerators, a Varian 600C (V6) and two Asea Brown Boveri (ABB) machines (LA6 and LA20). V6 and LA6 operate at 6 MV. LA20 is a dual energy accelerator and operates at 6 and 16 MV. All patients were planned using Varian Cadplan (v2.62 and later updated to 3.0.6) and prescribed to 100% at the isocentre. The number of monitor units and expected entrance doses were calculated by the treatment planning system.

A full description of the detector system, calibration procedure, correction factors applied and measurement procedure can be found in our previous paper.[12]

Radiotherapy techniques

Categories for differential analysis were determined to assist assessment of radiotherapy techniques and aid development of an appropriate action protocol. These were:

1. breast/chest wall
2. head and neck and brain with beam direction shell
3. isocentric pelvis and abdomen
4. isocentric intra-thoracic

Although radiotherapy techniques for any given treatment site varied according to individual patient requirements, the main principles of typical treatment approaches are outlined below. All techniques were isocentric unless otherwise stated:

- Patients with breast malignancies were treated using wedged medial and glancing fields to the breast/chest wall with a non-divergent dorsal edge. Symmetrical fields were used in all cases. During the period of measurements a commercially available breast positioning board replaced the use of a simple in-house designed device. The majority of patients were treated on LA6.
- Patients treated radically for head and neck and brain malignancies were immobilised in beam direction shells (with most of the field region cut out). Beam arrangements were either coaxial opposed, oblique wedged pair or 3 field

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combinations. The majority of fields were wedged. Shielding was employed for numerous patients. Wax build up was attached to shells for some patients (usually larynx patients). The majority of patients were treated on V6.

- The majority of patients with pelvic malignancies were treated with either a 3 field combination or a 4 field box technique. Patients were positioned in either the supine or prone position depending on the type of tumour. No pelvic immobilisation device was used. The majority of patients were treated on LA20.
- Patients irradiated radically for intra-thoracic malignancies were usually treated with a combination of 3 fields with 1 or more fields wedged. An in-house designed positioning device was used to maintain and reproduce arm position.

RESULTS

The results for entrance dose measurements as a whole (n = 2230) and the estimated overall errors for 578 treatments (incorporating all techniques and based on the weighted average of deviations) have been presented and discussed.[12]

Tables 1 and 2 summarise the results for different treatment sites/techniques and different equipment. Table 1 also contains the results for all

Table 1. *Summary of results of entrance dose measurements as a function of treatment site/technique*

Treatment site/technique		Number	% Mean	% SD	% ≥ 4%	% ≥ 5%
All fields		2230	0.77	2.85	16.7	9.2
All (estimated overall error in dose delivery)		578	0.69	1.96	4.8	2.4
All wedged fields		1090	0.89	3.03	20.7	10.8
All open fields		1140	0.66	2.66	13.0	7.7
Breast:	All fields	1073	1.15	3.04	22.2	12.5
	Wedge: Yes	567	0.97	3.15	23.3	12.0
	Wedge: No	506	1.35	2.89	20.9	13.0
	In-house board (old)	835	1.25	3.23	25.7	14.7
	Commercial board (new)	238	0.81	2.41	9.7	5.5
Head & neck and brain:	All fields	326	0.35	2.20	6.4	2.5
in BDS	Wedge: Yes	244	0.45	2.29	7.8	3.3
	Wedge: No	82	0.04	1.88	2.4	0
Isocentric abdomino-pelvic:	All fields	712	0.52	2.75	13.1	8.4
	Wedge: Yes	227	1.40	3.25	26.4	17.6
	Wedge: No	485	0.11	2.37	6.8	4.1
Isocentric intra-thoracic:	All fields	119	−0.01	2.75	18.5	3.4
	Wedge: Yes	52	−0.18	3.08	28.8	3.8
	Wedge: No	67	0.11	2.45	10.4	3.0

Table 2. *Summary of results of entrance dose measurements for different treatment equipment*

Machine and energy		Number	% Mean	% SD	% ≥4%	% ≥ 5%
LA6 (6 MV):	All fields	1136	1.10	3.03	21.8	12.0
	Wedge: Yes	535	0.93	3.23	24.9	12.5
	Wedge: No	601	1.25	2.82	19.1	11.5
LA20 (6 MV):	All fields	227	−0.14	2.85	12.3	8.4
	Wedge: Yes	54	−0.91	2.97	20.4	13.0
	Wedge: No	173	0.09	2.77	9.8	6.9
LA20 (16 MV):	All fields	494	0.72	2.68	13.8	8.3
	Wedge: Yes	206	1.78	3.04	26.2	16.5
	Wedge: No	288	−0.04	2.08	4.9	2.4
V6 (6 MV):	All fields	373	0.39	2.27	8.0	2.7
	Wedge: Yes	295	0.51	2.35	9.5	3.4
	Wedge: No	78	−0.06	1.88	2.6	0

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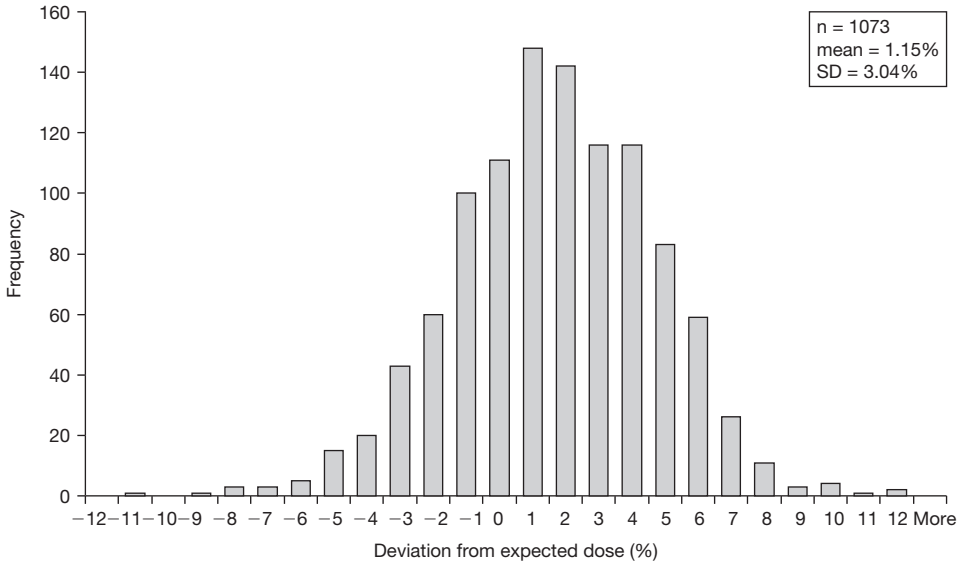


Figure 1. Frequency distribution of deviations from expected dose for entrance dose measurements on breast patients.

readings and wedged/plain fields as previously presented[12] to assist in comparing the findings for the various techniques studied here. A tolerance level of 4% was applied for all fields during the measurement period.

Breast techniques

A systematic deviation from 0% of +1.15 ($p < 0.0001$) was seen. The deviations detected are plotted in Figure 1. The mean deviation for this treatment site was significantly different from all other sites ($p < 0.0001$). In addition, the spread of deviations seen for this site (SD = 3.04%) was significantly higher than that seen for all readings without this category included ($p < 0.0001$).

Deviations $\geq \pm 4\%$ were detected in 238 measurements (22.2%). This represents a much higher number of large deviations than calculated for all readings *except* breast techniques (11.8% $\geq \pm 4\%$, n = 1157).

During the measurement period the breast technique was improved and a new patient positioning 'breast board' was implemented. Comparison of in vivo measurements for the different groups (commercial board versus simple in-house developed board) revealed significant differences. Results for the fields treated on the older board showed a mean deviation of 1.25% ± 3.23% (n = 835). In contrast the results for those fields treated on the new board showed a mean deviation of 0.81% ± 2.41% (n = 238). The reduction in the spread of deviations was significant ($p < 0.0001$). Furthermore a large reduction in the number of deviations $\geq \pm 4\%$ was seen (25.7% for the older technique reduced to 9.7% for the new one).

Head & neck and brain techniques in beam direction shells

The deviations detected are plotted in Figure 2. The SD of 2.20% is the lowest of the four treatment site categories analysed and reflects a smaller number of random errors in both treatment set-up and dose measurement technique.

Most of the larger deviations occurred in wedged fields. The 3 largest deviations were attributed to difficulty in positioning the detector in fields with very high angle of incidence.

Isocentric abdomino-pelvic techniques

The deviations detected are plotted in Figure 3. Large, statistically significant differences were seen

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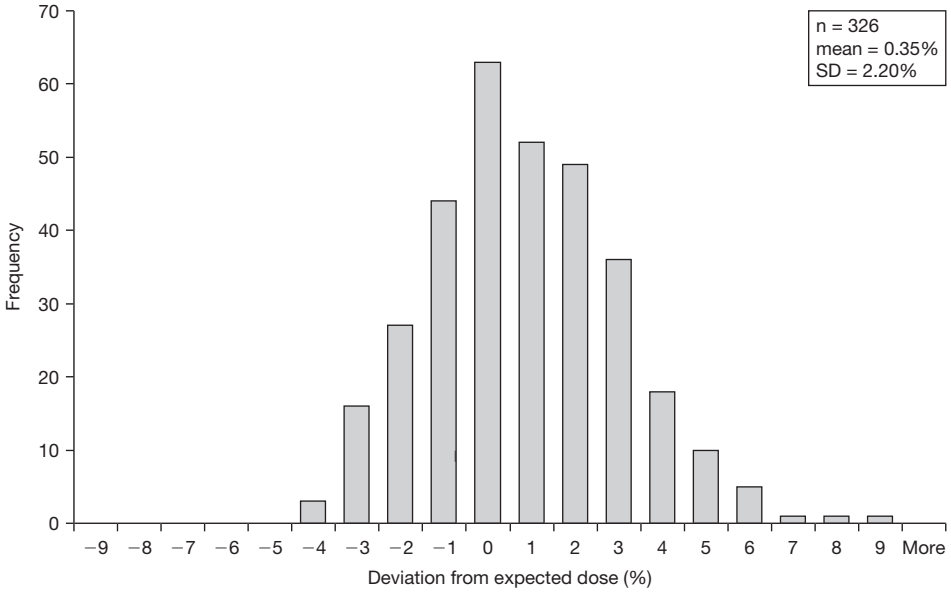


Figure 2. Frequency distribution of deviations from expected dose for measurements on head and neck techniques in beam direction shells.

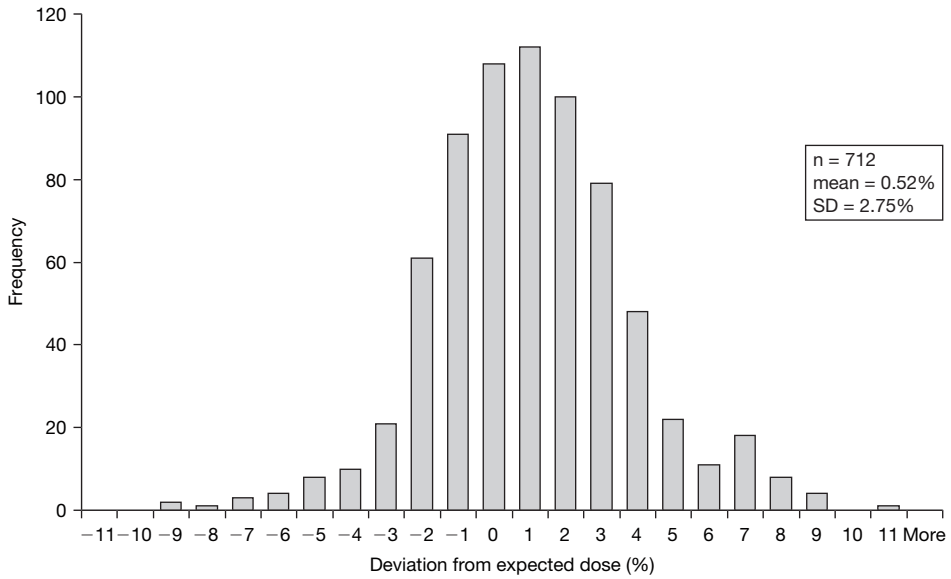


Figure 3. Frequency of deviations from expected dose for entrance dose measurements on isocentric abdomino-pelvic techniques.

between wedged and open fields. A systematic deviation of 1.4% was seen ($p < 0.0001$) for wedged fields compared to a small deviation (not significant) of 0.11% for open fields. A significantly larger SD was also seen for wedged fields (3.25% compared to 2.37%, $p < 0.0001$).

Most measurements exceeding tolerance occurred in wedged fields.

Isocentric intra-thoracic techniques

This category represented the smallest group with 119 measurements. The results are plotted in Figure 4 and show a somewhat random distribution.

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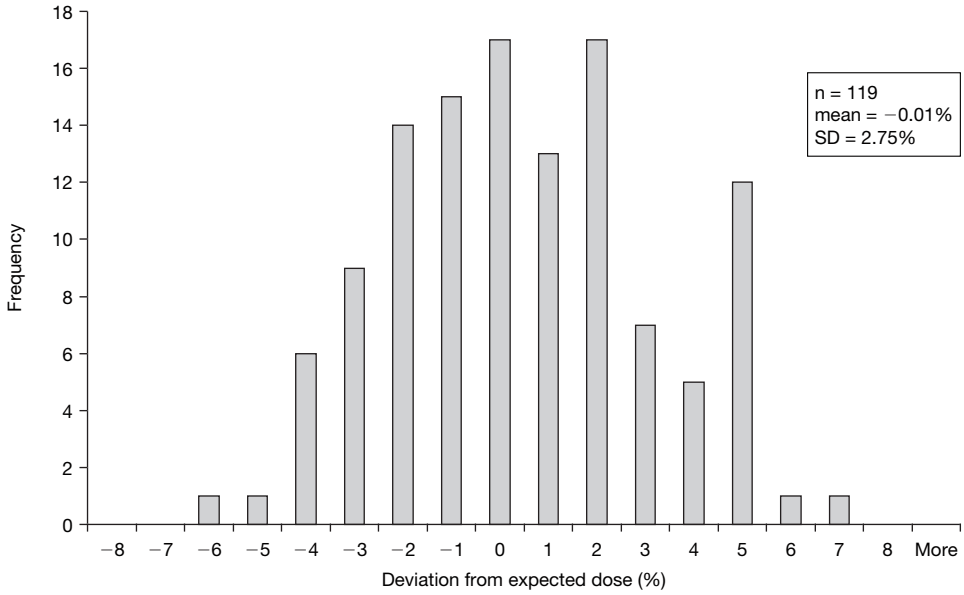


Figure 4. Frequency distribution of deviations from expected dose for entrance dose measurements on isocentric intra-thoracic techniques.

DISCUSSION

Breast techniques

Most patients with breast malignancies were treated on LA6, which over the measurement period showed a systematically high output (mean = +0.44%). This probably accounted for part of the systematic deviation of +1.15% for this treatment site. However, the largest contributory factor to this positive deviation was the systematic error noted in positioning detectors under conditions of oblique incidence described in our previous paper.[12] Incorrect placement in this manner will always have resulted in an overestimation of the dose as the detector would have been placed both towards the 'thin end' of the wedged field and closer to the target. The problem was addressed and an analysis of measurements over time (Fig. 5) verifies the extent of the contribution towards the systematic deviation and the consequent improvement. A point to note is that, prior to its correction, this positioning error will have contributed to a number of readings exceeding the upper tolerance limit. When action was triggered at the 4% level sources of error were very difficult to identify.

The SD of 3.04% was comparable with that reported in other similar studies.[16,24] The phasing in of a new, adapted technique employing a commercial 'breast board' produced a significant reduction in SD when the results were compared for the different techniques (from 3.23% to 2.41%, $p < 0.0001$). This suggested improvements in set-up reproducibility rather than coincidental improvements in diode measurement uncertainty as no comparable reduction in SD was noted for other treatment sites. IVD in this case has therefore confirmed an apparent improvement in treatment quality for this category of patient.

Head & neck in beam direction shell

The SD of 2.2% for these techniques is somewhat smaller than that seen for other categories and indicates a high level of reproducibility. This result compares favourably with reported values from similar studies.[9,17,20,24] The number of measurements exceeding tolerance is also in accord with previous published work.[17] The largest deviations were attributed to measurement difficulty in a highly oblique field and on repeat were within tolerance.

Although the overall mean deviation was small (+0.35%) and not found to be significant, further investigation highlighted 3 factors that would have systematically influenced diode reading but not

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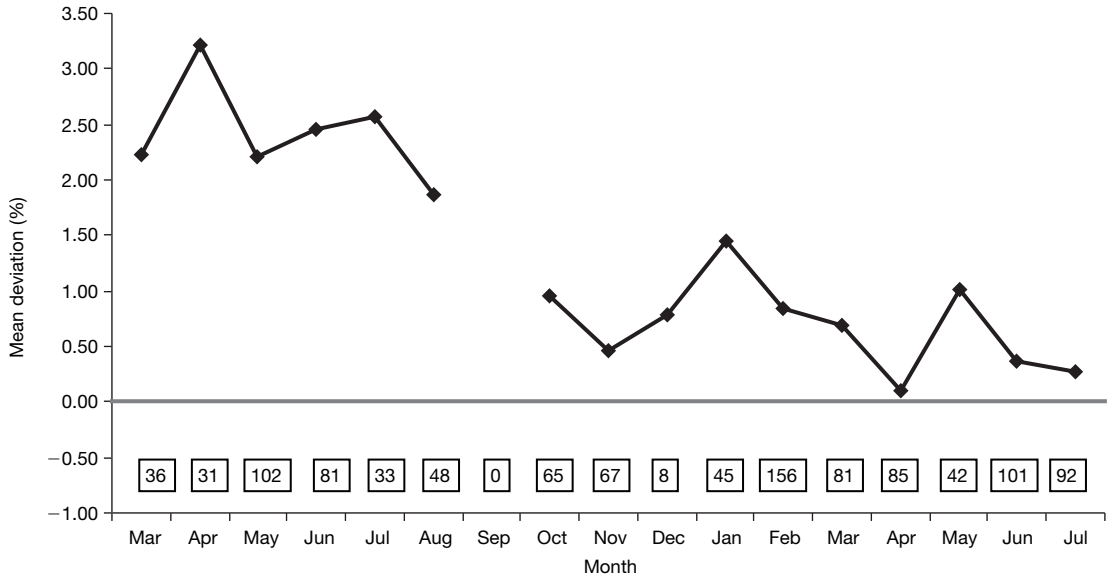


Figure 5. Mean deviations from expected dose for measurements on breast techniques. The chart confirms the effect of a systematic detector positioning error during the early part of the period. The data labels represent the total number of measurements made each month. The reason for the absence of measurements in September is unknown.

dose delivery to the target. Firstly the detector positioning error previously described would have resulted in systematically high readings during the early part of the measurement period where AOI was high (approximately 10% of measurements at that time). Secondly, the patient contour used for planning was taken from the inside of the BDS, whilst detectors were placed on the outside of it. This small systematic shift towards the target (≈2 mm) would have caused a small increase in reading of around 0.4% for the FSDs typically seen for these treatments. Thirdly, a significantly higher mean deviation for wedged fields (+0.51%) compared to open fields (−0.06%) for measurements made on V6 was noted ($p < 0.03$). Although this could be taken to confirm the error resulting from the incorrect positioning it probably also indicated that for measurements made underneath physical wedges on V6 the diode response was affected by increased scatter reaching the surface of the patient. This effect had not been corrected for.

Isocentric abdomino-pelvic techniques

The most important finding for this category was the significant difference between wedged and open fields (Table 1).

These differences were mirrored even more markedly when comparing 16 MV and 6 MV beams on the same unit and confirmed a variation in diode response under short FSD, physically wedged conditions at that energy that had not been identified and corrected for at the commissioning stage. The analysis of IVD has therefore been very useful in identifying this and prompted full evaluation and subsequent correction.

In almost two thirds of cases the placement of the detector on the anterior field was complicated by hair and this often resulted in the detector being 'sprung' slightly towards the target resulting in a higher than expected dose reading.

The SD of 2.75% noted for this category demonstrates acceptable levels of variation and is consistent with other recent reports.[24] However it should be noted that the SD may have been further reduced if an EDP-30 detector were used at 16 MV rather than the EDP-20. Although the manufacturers quote a beam energy range of 8–16 MV for the EDP-20, the water equivalent depth of measurement is 20 mm and thus at 16 MV the detector will be measuring dose in the build-up region – i.e. in a steep dose gradient – and so uncertainty in dose measurement increases.

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For this particular category, 8.4% of all measurements were greater than 5% from the expected dose. This is comparable with the only (recent) similar quantified data for entrance dose measurements on pelvic patients[24] where 10.7% were noted to have exceeded a 5% level.

Isocentric intra-thoracic techniques

These treatments occurred infrequently with the 119 measurements being based on only 28 different patients some of which required repeats. The spread of measurements was identical to that seen in the abdomino-pelvic treatments, which seems to suggest that the effects of breathing on measurement accuracy are not significantly different in either category and that similar problems were experienced in terms of IVD as a whole for both groups of patients. It was noted that greater uncertainty in FSD accuracy existed for this category of treatments.

Tolerance levels and action protocol

In order to determine appropriate tolerance levels the uncertainty related to diode measurement *in practice* (i.e. not solely based on measurements made during the commissioning process) needed to be established. In estimating the measurement uncertainty associated in our series of measurements the maximum expected deviations (taken as 1 SD) related to diode calibration against the ionisation chamber, variations in diode sensitivity between monthly calibrations, machine output variations, AOI and temperature correction, treatment FSD variations, detector positioning, field size and electrometer precision were determined. In addition to these factors, the analysis of measurements indicated a variation in diode response under short FSD, physically wedged conditions at 16 MV. This resultant uncertainty was also established.

Table 3 shows the statistical uncertainty in dose measurement (based on a square root estimation) for the 4 different treatment categories. Where maximum expected variations could not be specifically determined for treatment sites but equipment instead (e.g. machine output) then the uncertainty for a technique was assumed to be that for the equipment most commonly used for that treatment site (i.e. breast techniques – LA6, abdomino-pelvic and intra-thoracic – LA20 16 MV, head and neck – V6).

Table 3. *Dose measurement uncertainty associated with different treatment sites for wedged and open fields over measurement period*

	Statistical uncertainty			
	Breast (%)	**Head & neck (%)**	**Abdomino-pelvic (%)**	**Intra-thoracic (%)**
Wedged fields	3.47	3.03	3.50‡	5.84‡,§
Open fields	3.13	2.86	3.00	5.56§

‡ This value could be reduced if a variation in diode response under wedged fields at 16 MV was corrected for.
§ These values are larger mainly as a consequence of a relatively higher proportion of FSD inaccuracies for this category. Improvements in this respect would reduce these figures to the level seen for isocentric abdomino-pelvic techniques.

For breast, head & neck and abdomino-pelvic these uncertainties (taken as 1 SD) are slightly larger than the spreads seen in the results for different treatment categories (Table 1) which seems to suggest that variations within 1 SD are largely due to measurement uncertainty. For intra-thoracic treatments the uncertainty in measurement is around twice the SD noted for that category (attributable to greater uncertainty in FSD accuracy). In general, this analysis has shown that, with the exception of the intra-thoracic category, the 4% tolerance level did exceed the measurement uncertainty but probably not by a substantial enough amount. This perhaps goes some way to explaining why, in those instances where deviations exceeding 4% (but not significantly) were investigated, it was very difficult to identify any obvious sources of error.

An important factor to take into account is the number of measurements falling outside a predetermined action level and requiring repeats. If this number is high, then staff may begin to question the aim of IVD and lose faith in its value as a QA tool. The impact of 'tight' tolerances on staff workload is clear. Indeed this effect did seem to be apparent during this work where some radiographers were unhappy with the number of repeats required and became somewhat disillusioned about the programme. This may have contributed to those occasions where measurements outside the 4% tolerance were accepted without repeat.

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It may also have contributed to insufficient investigation into deviations exceeding tolerance, even when the deviations were quite large (at least 8 deviations greater than 7% from expected dose were repeated without any obvious investigation having taken place). This approach is of concern in that large errors in dose delivery of any clinically significant magnitude cannot be detected, and therefore corrected, if deviations are not investigated. It is, though, understandable if radiographers begin to perceive that they will not identify any clear reasons for the deviations, particularly when under pressure to maintain patient throughput. For this reason tolerance levels should minimise the number of repeats required resulting from small, random variations in treatment set-up and acceptable uncertainties in dose measurement. However, it is imperative that high numbers of 'large' deviations are not simply and automatically interpreted as random, acceptable variations when in fact they may be pointing in the direction of sub-optimal set-up or dose measurement procedure. The balance is a fine one and although ultimately the long-term goal should be to keep tolerances as low as practically achievable through minimising measurement uncertainties, the factors above should also be accounted for.

A final consideration in deciding on appropriate tolerance levels was the overall spread of results. In general, the histograms for entrance dose measurements (Figs. 1–4) for all treatment sites except isocentric intra-thoracic were normally distributed indicating that approximately 95% of measurements were within 2 SD. A large error may be considered, statistically, to be one greater than 2 SD from the mean and some studies have justified a tolerance level of 5% on the basis that it approximates to 2 SD.

Based on the findings of this work it is reasonable to suggest that different action/alert levels should be implemented for different categories of treatment site. Moreover, it appears necessary to increase tolerance levels. It is important to keep any action protocol relatively simple as complicated multilevel tolerances may cause confusion and give rise to problems through incorrect levels being applied. For example, applying different tolerances for wedged portions of fields as well as for different treatment sites would not be appropriate.

With regard to the action taken in the event of a deviation exceeding tolerance it was clear that in a number of instances the protocol was not being adequately followed, most probably as a consequence of tolerances being too narrow as discussed above. In any event, non-compliance potentially undermines the ultimate aim of IVD in identifying clinically important errors in dose delivery. It was recognised, therefore, that both tolerance levels for entrance dose measurements and the associated action required appropriate adjustment to produce a positive shift in approach. An action protocol combining tolerances for single fields and estimated overall error as described in our previous paper[12] would also be desirable.

CONCLUSIONS

As our previous paper[12] highlighted it was clear that variations between measured and expected doses were mainly due to factors affecting diode reading rather than actual dose delivery. For breast and head & neck techniques a systematic error in detector positioning resulted in erroneous dose measurements during the early stages of the measurement period but was corrected. For abdomino-pelvic techniques, particularly those at 16 MV and also to some extent head and neck techniques, variation in diode response under short FSD, wedged fields was noted that had not been corrected for. This work has prompted subsequent evaluation. Once implemented then measurement uncertainty for abdomino-pelvic techniques will reduce further.

The use of an EDP-30 detector for 16 MV beams may also have reduced uncertainty through avoiding measuring dose in the build-up region. Alternatively, the continued use of the EDP-20 detector is justified assuming wider tolerances are adopted and/or correction for field size is considered[4] (following further evaluation of its response in 16 MV beams).

Important conclusions about tolerance levels and action protocol can be reached as a consequence of this work. In general the tolerance levels implemented can be considered to have been too low given the level of measurement uncertainty and the impact of the number of repeats required. The consequence of this was the

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Table 4. *Recommended action protocol with revised tolerance levels*

Site/technique	Tolerance level (%)	Action
Single field entrance doses		Radiographer ± physicist ± consultant
Breast	6‡	1. check diode position and attachment;
Head & neck in BDS	5§	2. check of treatment parameters with patient on treatment couch;
Any: 16 MV	6†	3. check MU calculation;
All other sites	5	4. record comments/reasons for deviation;
Estimated error at isocentre		5. repeat measurement for field at next fraction (or all fields if estimated overall error exceeds tolerance).
All treatments	4	If deviation still larger than tolerance after 2 repeats (3 measurements) and no reason identified then decision to accept/investigate further to be made by consultant.

‡ With a view to reduce to 5% when improved accuracy through use of commercial breast board is fully established.
§ With a view to reduce to 4% following correction of diode response under short FSD, wedged fields.
† With a view to reduce to 5% following correction of diode response under short FSD, wedged fields and the possible use of an EDP-30 detector.
NB Action to be triggered if either single field exceeds tolerance OR estimated overall error exceeds tolerance.

inconsistent application of the action protocol thus potentially detracting from an important aim of IVD – identifying and correcting errors. Paradoxically, therefore, a widening of tolerances might actually improve global quality of procedure *and* treatment as investigation of *important* errors is facilitated and identification of sources of the errors becomes more straightforward. However, it is important to stress that tolerances are not so wide as to risk not identifying important errors and in any event it is strongly recommended that an action protocol is rigorously applied with deviations consistently investigated.

As a result of the different uncertainties associated with each treatment site/technique different tolerance levels for entrance dose measurements are recommended for each. A summary of the recommended action protocol is shown in Table 4.

For breast techniques a tolerance of 6% is suggested, this being sufficiently greater than the expected measurement uncertainty to identify inaccuracies and equal to 2 SD. However, given the improvements in results noted following the introduction of a new 'breast board', consideration may be given to reducing this to 5% when confidence in terms of improved accuracy of treatment delivery is fully established.

For head & neck techniques using a BDS, only relatively few readings (6.4%) were outside tolerance. An expected measurement uncertainty of up to 3% was not substantially lower than the 4% tolerance although this uncertainty would reduce if variations in diode response under wedged fields were corrected for. Consequently a tolerance of 5% is recommended with a view to reducing this back to 4% following further evaluation and subsequent correction. It is considered especially appropriate to attempt to maintain a 4% action level for this category given the number and proximity of class 1 and 2 organs at risk to high dose volumes.

For isocentric abdomino-pelvic and intra-thoracic techniques, measurement uncertainty was relatively high as a consequence of the increase in response of the diodes in short FSD, wedged fields. By far the greatest effect was noted for the EDP-20 detector in 16 MV beams. It was difficult to identify any other direct sources of unexpected dose reading, further underlining the too narrow gap between the determined measurement uncertainty and tolerance. It is suggested that a tolerance of 6% is applied for any treatment using 16 MV with a view to reducing this to 5% following further evaluation and correction as described previously.

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Our previous paper[12] suggested that an assessment of the estimated combined error in dose delivery for all fields is potentially useful in evaluating the overall dosimetric accuracy for a treatment. This is particularly true if tolerance levels for entrance dose measurements were to be extended. Continued estimation of this error from entrance dose measurements alone using a weighted average method[16] or (preferably) the use of TMR data is recommended. A suggested tolerance of 4% is proposed, on the basis of both clinical accuracy requirements[26,27] and the results previously described.[12]

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References

1. Essers M, Mijnheer BJ. In vivo dosimetry during external photon beam radiotherapy. International Journal of Radiation, Oncology, Biology and Physics 1999; 43(2):245–259.
2. Grusell E, Rikner G. Evaluation of temperature effects in p-type silicon detectors. Physics in Medicine and Biology 1986; 31:527–534.
3. Rikner G, Grusell E. General specifications for silicon semiconductors for use in radiation dosimetry. Physics in Medicine and Biology 1987; 32:1109–1117.
4. Rikner G, Grusell E. Patient dose measurements in photon fields by means of silicon semiconductor detectors. Medical Physics 1987; 14(5):870–873.
5. Nilsson B, Ruden BI, Sorcini B. Characteristics of silicon diodes as patient dosimeters in external radiotherapy. Radiotherapy and Oncology 1988; 11:279–288.
6. Rikner G. Compendium on semiconductor detectors. 1994 Uppsala, Sweden.
7. Howlett SJ, Kron T. Evaluation of p-type semiconductor diodes for in vivo dosimetry in a 6 MV X-ray beam. Australasian Physical and Engineering 1996; 19(2): 83–93.
8. Sen A, Parsai EI, McNeeley SW, Ayyangar KM. Quantitative assessment of beam perturbations caused by silicon diodes used for in vivo dosimetry. Int J Radiat Oncol Biol Phys 1996; 36(1):205–211.
9. Loncol T, Greffe JL, Vynckier S, Scalliet P. Entrance and exit dose measurements with semiconductors and thermoluminescent dosemeters: A comparison of methods and in vivo results. Radiotherapy and Oncology 1996; 41(2): 179–187.
10. Meiler RJ, Podgorsak MB. Characterisation of the response of commercial diode detectors used for in vivo dosimetry. Medical Dosimetry 1997; 22(1):31–37.
11. Georg D, De Ost B, Hoornaert M-T, Pilette P, Van Dam J, Van Dycke M, Huyskens D. Build-up modification of commercial diodes for entrance dose measurements in 'higher energy' photon beams. Radiotherapy and Oncology 1999; 51:249–256.
12. Appleyard RM, Ball K, Hughes FE, Kilby W, Lassen S, Nicholls R, Rabett V, Sage J, Smith M, Thomson E. Systematic in vivo dosimetry for quality assurance using diodes 1: Experiences and results of the implementation of entrance dose measurements. Journal of Radiotherapy in Practice 2004; 3(4):185–196.
13. Essers M, Lanson JH, Mijnheer BJ. In vivo dosimetry during conformal therapy of prostatic cancer. Radiotherapy and Oncology 1993; 29:271–279.
14. Noel A, Aletti P, Bey P, Malissard L. Detection of errors in individual patients in radiotherapy by systematic in vivo dosimetry. Radiotherapy and Oncology 1995; 34:144–151.
15. Chun Li, Lamel LS, Tom D. A patient dose verification program using diode detectors. Medical Dosimetry 1995; 20(3):209–214.
16. Adeyemi A, Lord J. An audit of radiotherapy patient doses measured with in vivo semiconductor detectors. British Journal of Radiology 1997; 70:399–408.
17. Blyth C, McLeod AS, Thwaites DI. A pilot study of the use of in vivo diode dosimetry for quality assurance in radiotherapy. Radiography 1997; 3:131–142.
18. Calandrino R, Mauro Cattaneo G, Fiorino C, Longobardi B, Mangili P, Signorotto P. Detection of systematic errors in external beam radiotherapy before treatment delivery. Radiotherapy and Oncology 1997; 45:271–274.
19. Cozzi L, Fogliata-Cozzi A. Quality assurance in radiation oncology. A study of feasibility and impact on action levels of an in vivo dosimetry program during breast cancer irradiation. Radiotherapy and Oncology 1998; 47:29–36.
20. Millwater CJ, MacLeod AS, Thwaites DI. In vivo semiconductor dosimetry as part of routine quality assurance. British Journal of Radiology 1998; 71:661–668.
21. Wolff T, Carter S, Langmack KA, Twyman NI. Characterization and use of a commercial n-type diode system. British Journal of Radiology 1998; 71:1168–1177.
22. Voordeckers M, Goossens H, Rutten J, Van den Bogaert W. The implementation of in vivo dosimetry in a small radiotherapy department. Radiotherapy and Oncology 1998; 47: 45–48.
23. Shakeshaft JT, Morgan HM, Simpson PD. In vivo dosimetry using diodes as a quality control tool – Experience of 2 years and 2000 patients. British Journal of Radiology 1999; 72:891–895.
24. Fiorino C, Corletto D, Mangili P, Broggi S, Bonini A, Mauro Cattanaeo G, Parisi R, Rosso A, Signorotto P, Villa E, Calandrino R. Quality assurance by systematic in vivo dosimetry: Results

https://doi.org/10.1017/S1460396905000208 Published online by Cambridge University Press

on a large cohort of patients. Radiotherapy and Oncology 2000; 56:85–95.

25. International Commission on Radiation Units and Measurements. Determination of absorbed dose in a patient irradiated by beams of X or gamma rays in radiotherapy procedures, Report 24. Washington DC: ICRU publications, 1976.
26. Mijnheer BJ, Batterman JJ, Wambersie A. What degree of accuracy is required and can be achieved in photon and neutron therapy? Radiotherapy and Oncology 1987; 8:237–252.
27. Brahme A, Chavaudra J, Landberg T, McCullough E, Nusslin F, Rawlinson A, Svensson G, Svensson H. Accuracy requirements and quality assurance of external beam therapy with photons and electrons. *Acta Oncologica* 1988; Suppl.

https://doi.org/10.1017/S1460396905000208 Published online by Cambridge University Press