Journal of Radiotherapy in Practice

Journal of Radiotherapy in Practice (2012)
11, 55–61

doi:10.1017/S1460396911000082

Literature Review

In vivo dosimetry; essential or unnecessary?

Jenna L Leman

Radiotherapy Department, Southampton Oncology Centre Level A, Southampton General Hospital, Southampton, UK

Abstract

Introduction: The radiotherapy profession has learned from errors made during treatment planning and delivery. Quality assurance in radiotherapy (QART) procedures are implemented to reduce the risk of an error occuring. The chief medical officer, along with others, has recommended that the QART of all departments includes *in vivo* dosimetry (IVD) to ensure that the delivered dose equals the planned dose.

Why we need IVD: A lot of effort goes into field verification and it is just as vital that dosimetry is verified. Overdose to normal tissue can cause devastating side effects, even death, whilst tumour underdose may compromise control. Without IVD, there is no way of knowing that a patient is receiving an overdose until it is too late. Underdoses are unlikely to manifest without IVD. IVD allows radiotherapists and physicists to correct for dose errors in a timely manner.

Why IVD is unnecessary: Radiotherapy accidents are rare. Implementing IVD is expensive, time consuming and takes resources away from developing techniques which will improve patient outcomes. Current IVD methods are not suitable for modern techniques such as intensity modulated radiotherapy (IMRT).

Discussion: IVD appears to be a useful QART tool, particularly as dose escalation techniques develop allowing a higher dose to be delivered to the tumour. Departments may be unwilling to spend time and money on an IVD system that is costly and time consuming if it cannot perform IVD on modern techniques. Electronic portal imaging devices (EPIDs) can be utilised to perform IVD on complex techniques, such as IMRT and arc therapy, which current IVD methods cannot, however there is currently no EPID IVD system available commercially.

Conclusion: Ideally, all departments would conduct IVD on all new patients. IVD has proven to be an important QART tool, however, until technology is developed to allow EPID to include IVD, the procedure is not likely to be implemented countrywide.

Keywords

Radiotherapy; *in vivo* dosimetry; dose verification; dosimetry verification; treatment verification; dosimetric QA; radiotherapy QA

Correspondence to: Jenna L Leman, Radiotherapy Department, Southampton Oncology Centre Level A, Southampton General Hospital, Tremona road, Southampton, UK. E-mail: Jenna.Leman@SUHT.SWEST.NHS.UK

INTRODUCTION

Radiotherapy has played a part in the treatment of cancer in the UK for a century[1] initially as a

rather novel, experimental modality. Now, radiotherapy is an important part of cancer treatment, with 40% of patients receiving radiotherapy as part of their treatment.[2]

Over the years, radiation accidents causing severe side effects and even death have highlighted the need for quality assurance in radiotherapy (QART). This relates to all aspects of the patient's journey through radiotherapy, from radiation prescription to the final treatment and follow-up.[3] Major overdoses occur in the absence of written protocol and checking procedures, therefore QART is crucial to ensure the safe delivery of radiotherapy.[3]

Currently, in the UK, all departments implement QART and radiation overdoses greater than 10% of the prescribed course (or 20% of one fraction) are reportable under the Ionising Radiation (Medical Exposure) Regulations (IR(ME)R). Underdoses are not, even though they may lead to inadequate tumour control. It has been suggested that underdoses are harder to detect, particularly as complications caused by overdose usually manifest whilst the patient is on treatment, whereas underdoses are less obvious.[4]

The potential risks and complications of radiotherapy have been well documented and assessed for emerging treatment techniques.[5,6] All patients undergoing radiotherapy are advised of the potential side effects and long-term complications during the consent process and are given information on how to cope with them.[7] Common early effects are generally observed in tissues with rapid cell proliferation, such as the skin and bowel, whereas late effects, such as telangiectasia and radiation-induced cancers, can happen many years after completing a course of radiotherapy.[8] Radiation overdose causes early onset and increased severity of acute side effects, as well as amplifying late effects.[8]

QART is now an integral part of radiotherapy in the UK and was developed to reduce radiotherapy accidents, including radiation under or overdose. With the effects of incorrect dosimetry so devastating, even life threatening on occasion, it follows that dose verification should be an important part of QART. UK departments test machine outputs on a daily basis and have a rigorous checking procedure for the planning stages. It could be argued that it is equally important to check patients' treatment plans during treatment to ensure that the dose received by each field is as planned. *In vivo* dosimetry (IVD) provides us with a mechanism in which to conduct this important check and various methods are available, including diodes and thermo luminescent detectors (TLDs) which are explained in more detail below.

In his annual report, the Chief Medical Officer, Sir Liam Donaldson, stated that IVD offers 'an opportunity to add another safeguard in the process of care to protect patients'.[9] A report published by the Royal College of Radiologists (RCR) recommends that all departments implement IVD protocols, conducting IVD measurements for patients at their first fraction.[10] The report states that IVD has the potential to detect dosimetric errors, for example, the use of an incorrect wedge, in time for corrective action to take place, thus reducing patient harm. Despite the recommendations, only 30–40% of UK radiotherapy centres[11] conduct IVD and this is not increasing rapidly.[12] Cost, time and effectiveness have been blamed for the slow uptake of IVD.[11] This paper will put forward the arguments for and against implementing IVD, provide a balanced discussion and attempt to conclude whether or not IVD is a worthwhile investment.

METHODS OF CONDUCTING IVD

TLDs

These devices usually contain lithium fluoride, or a similar material, which absorbs and stores the energy of an x-ray beam. Upon heating, the TLD emits the energy absorbed from the x-rays in the form of light, which can be measured by a photomultiplier tube.[13] In practice, the device would be placed in the centre of the radiation field to absorb the x-rays as they are delivered. The device is then sent off for processing by a photomultiplier tube and the dose delivered can be recorded.

https://doi.org/10.1017/S1460396911000082 Published online by Cambridge University Press

Semiconductor diodes

Semiconductor diodes are the preferred method of conducting IVD as the reading is available immediately. The diodes are made from silicon placed in a small, solid case and are also used by placing in the radiation field. During irradiation, ionisations occur within the detector which can be measured by the current they generate.[13] The result is viewed digitally on a computer monitor via specialist software.

Electronic portal imaging device (EPID)

EPID technology is currently available for field verification via portal imaging. Recent research[14] shows that the pixel grey levels on the images produced can also be used to determine exit dose. Although this is a promising development in IVD technology, no system for EPID IVD is currently available.

THE ARGUMENT FOR: IVD IS AN ESSENTIAL PART OF QA

In radiotherapy, there are many factors that may contribute to occurrence of an error.[15] QART guidelines aim to reduce the possibility of an error occuring and the reporting of incidents allows us to learn from previous mistakes. But, as we know from the media and IR(ME)R reported incidents, errors still occur. A total of 181 incidents occurred between May 2000 and August 2006.[10] A highly publicised[16] example of a radiation overdose happened in Glasgow in 2006 because the incorrect output figure was entered into the treatment planning system (TPS) and the senior planner who checked the plan failed to notice the mistake.[17] IVD would not prevent all radiation incidents, but it would allow us to discover a dose discrepancy in time to take corrective action.

Verification is an important aspect of QART, from confirming a patient's identification to independently checking monitor unit (MU) calculations. Geometric field verification, using portal images, account for a large proportion of the radiotherapists' workload. This is justified because it allows us to ensure that field placement is correct and creates a permanent record of where we are treating. Dose verification is just as important as it allows us to ensure that each field is receiving the planned dose.

Critical errors causing incorrect dose delivery occur all over the world. A review[18] investigated reported radiotherapy incidents over three decades, discovering 3,125 errors that caused harm to the patient. The authors admit that the results may be skewed as the recent introduction of QART has dramatically reduced error rates; but not all errors are reported and many may not even be discovered.

An RCR document[10] looked into IR(ME)R reported incidents and made some recommendations, many of which are beyond the scope of this paper. Here, we are interested in only one; that all radiotherapy departments introduce IVD at the beginning of treatment for most patients, excluding only those that meet clear departmental exclusion criteria.

Delivering the correct dose to the patient is essential. Adequate tumour control can be achieved if the dose is delivered as planned; whereas underdose may compromise tumour control. Overdose can cause debilitating or even fatal complications, as we have seen in the Glasgow incident.[16,17] The report on the investigation into the Glasgow incident recommends the use of IVD during the first fraction of radiotherapy, suggesting that the error could have been noticed after the first fraction.[17]

IVD can potentially detect dose errors before it is too late. Common dosimetry errors include wedge misuse, MU calculation error and incorrect machine calibration.[4] The use of IVD at the first fraction highlights dose errors, the cause can be investigated and corrective action taken, thus minimising harm to the patient.

An extensive study into IVD[19] reports on 5 years experience using IVD. The article appears to be valid as the authors were extremely stringent in the collection of their results, although its age must be taken into consideration. At the time, no record and verify system was available and the TPSs and machinery are likely to have been updated since the study began.

https://doi.org/10.1017/S1460396911000082 Published online by Cambridge University Press

Researchers conducted IVD at the central axis for each field. Factors affecting the dosimetry were corrected for, such as obliquity, wedges and source-skin distance, although temperature corrections were not made. Any measurements exceeding the 5% action level were referred to physicists, who checked and verified all treatment parameters before repeating IVD on the next fraction. If repeated measurements were out of tolerance, a plan check using IVD on a phantom was performed. This phantom check allowed physicists to ensure that there were no problems with the calibration of the machine or the TPS. The results showed that IVD was able to detect dose errors resulting from incorrect normalisation, wedge misuse and inaccurate data entry as well as changes in patient separation. During the 5 years, 11 major dose errors were found and corrected for. This may not seem like many, but if they had not been picked up by IVD each one would have been reportable to IR(ME)R and may have caused severe side effects for the patients. If the dose errors had not been picked up, and the patients had suffered unnecessarily, media attention and legal involvement may have occurred.

The authors draw valid conclusions from their investigation, stating that IVD is an important tool for QART. The results of the study suggest that IVD is important in discovering errors which may affect many patients if uncorrected, for example an error in the TPS.

It has been argued that the introduction of IVD is pointless, as the procedure is not a viable QART technique for modern treatment plans such as intensity modulated radiotherapy (IMRT) and image-guided radiotherapy (IGRT).[20] This paper, however, is merely the opinion of two people and the only reference used is Sir Liam Donaldson's recommendations for IVD. Without any evidence to back up their claims, this paper should be disregarded. Many other authors have researched the problems that complex techniques may pose to IVD and discovered 'future proof' methods. A recent paper[14] reviewed the literature available on the use of EPIDs for IVD. The literature search conducted for the review was not very thorough, only searching one journal database, using limited search terms and not stating inclusion or exclusion criteria. However, a large number of recent articles on the use of EPIDs for IVD were included. The review highlights a number of studies that suggest EPIDs can be used to verify the dose delivered to the patient during IMRT.[21–23] In their conclusion, the authors state that EPIDs are the best way to verify the dose delivered to IMRT patients, as other methods only measure point doses. This review shows that IVD is not only possible when delivering simple radiotherapy techniques.

Overall, QART has proven to be invaluable in protecting patients, and IVD is an important part of this. Dose verification must, therefore, be worth implementing in all departments, as recommended. Although initial costs may be high and workload is likely to be increased,[4] IVD is justified by the benefits. A report by the Institute of Physics and Engineering in Medicine (IPEM) conducted a cost-benefit analysis of IVD and concluded that the IVD is cost effective.[24] However, it is important to look at the arguments against IVD before drawing any conclusions.

THE ARGUMENT AGAINST: IVD IS EXPENSIVE AND UNNECESSARY

Radiotherapy is generally considered a safe treatment.[10] From May 2002 to August 2006, only 338 patients were involved in IR(ME)R reportable incidents and only 24 of them were likely to be severely clinically affected (three per 100,000). Patients are 69,000 times more likely to die from cancer than radiotherapy error and radiotherapy is much safer than surgery, hospital admission and chemotherapy.[4] It is unrealistic to expect all risk to be eliminated from a procedure as complex as radiotherapy, but as a profession we try to reduce risks as much as possible. IVD is yet another method of protecting the patient, but some papers[25] suggest that dose errors are picked up so infrequently that no overall improvement in patient outcome will be shown. The authors state that the IPEM report[24] is flawed and it is wrong to conclude that IVD is cost effective. They correctly point out the flaws

https://doi.org/10.1017/S1460396911000082 Published online by Cambridge University Press

in the IPEM model, for example, the model only evaluates underdoses and assumes that an underdose leads to death, however the authors go on to extrapolate the IPEM model to include overdoses and make their own assumptions, such as an overdose in one patient cancels out an underdose in another. Although models provide us with a scientifically valid method of testing a theory, as all extraneous variables are controlled, they lack ecological validity.[26] In reality, models only provide us with an idea of what may happen but we cannot assume they are reliable until tested in real life. Mckay and Williams'[25] paper appears to show that IVD may not be cost effective; however, their results come from a model that they have already shown to be flawed. The paper provides an interesting but unreliable theory, and goes on to suggest (without proof) that the reports recommending IVD are driven by politics and the media to improve public confidence in radiotherapy and the National Health Service (NHS).

Time, cost and effectiveness appear to be the reasons that IVD is still not routine in all hospitals for all patients.[24] Malicki et al.[27] attempted to assess the extra cost IVD implementation has on a radiotherapy department in Poland and compare it to the quality of radiotherapy, quantified by accuracy of irradiation. A total of 6864 patients were analysed over 4 years and mean deviations between planned and delivered dose appeared to decrease, suggesting that IVD was having an impact. Monthly radiotherapy costs more than doubled. The results state that after the initial costs of purchasing IVD equipment and software, labour was the most expensive factor. Physicists were required to calculate entrance doses, calibrate dosimeters and assess the plan on a phantom if IVD results were not as expected. Radiotherapists had to place dosimeters on the patients thus increasing appointment times and two extra radiotherapists were employed to assist with the extra workload. From the study, it would appear that IVD is expensive but it also increases the accuracy of radiotherapy. However, as the study lasted for 4 years, other improvements were made to the radiotherapy department and QA systems during that time so it is impossible to attribute the increased cost and accuracy to IVD alone. From this paper, even though we cannot quantify exactly how much time and money went into IVD, we can expect that the implementation of other new techniques may have suffered, as a result of IVD taking up resources.

A recent study[24] attempted to calculate the cost of diode IVD to an average department. The following costs were identified;

- Initial purchasing of diodes costs £6000 for a basic system.
- Linear accelerator capacity is reduced by 3%, assuming each patient's diodes take 5 minutes to set up.
- Staff must be trained to use diodes, at an average of 30 minutes per staff member, taking them away from their normal duties.
- Physics staff are required to calculate the dose each diode should receive, as well as investigating when IVD readings are not as expected and calibrating diodes on a monthly basis.

Using 2007 data, the paper suggests that IVD using diodes costs an average of £18,882 per linear accelerator per year. The authors arrive at this figure by making some assumptions and averages, all of which seem sensible. For example, they assume that placing diodes on the patient takes 5 minutes and they use midpoint of band 6 as an average for calculating staffing costs. Overall, the financial costs suggested by this paper appear to be reasonable and a valid guide. As a profession, we need to decide whether it is worth spending so much money to improve patient safety in a procedure that is relatively safe.[10]

DISCUSSION

Due to the many official recommendations,[3,9,10,17,30] it appears to be inevitable that eventually all departments will be conducting IVD. A short paper by the RCR provides recommendations on how IVD can gradually be introduced into departments to minimise the effect of IVD on linear accelerator capacity.[30] The paper recommends that departments begin IVD on a select group of patients, ideally treatments that carry a higher risk than others. Once

https://doi.org/10.1017/S1460396911000082 Published online by Cambridge University Press

the staff groups involved are confident conducting IVD, it can be phased in for other treatment categories. In the author's opinion, if the RCR recommendations are followed, there is no reason why IVD should become a burden to radiotherapy departments whilst they introduce the practice. Of course, there is likely to be some disruption, for example, staff having to leave the treatment units to undergo IVD training[24] but introducing IVD gradually, as recommended, will keep disruption to a minimum.

From a funding point of view, it is understandable why many radiotherapy departments are still not implementing IVD for all patients. With the NHS making cutbacks, all departments have to restrict their spending and it is reasonable that money should be spent for developing new techniques that could have a real impact on patient outcome, rather than further attempting to reduce errors in an already safe treatment.[10] However, in the current climate where the NHS is forced to hand out thousands of pounds in compensation claims,[28] it could also be argued that IVD is important in reducing patient risk. Although there is no proof that current IVD recommendations are motivated by politics and the media, going against these recommendations will not improve public confidence in our profession.

The most time consuming part of IVD using diodes is calibrating the diodes and calculating correction factors.[29] This time can be reduced by using TLDs instead of diodes, however, TLDs are more expensive and do not give online readings.[29] As most departments use portal imaging to verify patient position, and as EPIDs can be used in IVD, surely it makes sense to use this method of IVD. Modern techniques with steep dose gradients, such as IMRT, can be more accurately measured using EPID. Van Elmpt[14] suggests that EPID is a promising method of verifying dose to the patient, either as a pre-treatment exercise or *in vivo*, as complex procedures such as arc therapy, IGRT and IMRT can also undergo IVD. Once the systems are in place, analysis of the dosimetric data can potentially be automated, so radiographers and physicists incur limited extra work. However, it appears that there is a lack of commercial systems available utilising EPIDs as online IVD tools. The systems used in the literature are generally developed in-house and are confined to academic centres. This paper recommends that commercial systems are developed to utilise EPIDs for IVD, as departments are unlikely to invest in a system such as diodes which cannot accurately be used to verify dose in modern treatments. With radiotherapy becoming increasingly advanced and dose escalation increasing radiation prescriptions, it is more important than ever to ensure that the delivered dose equals the planned dose.

CONCLUSIONS

Those of us in the radiotherapy profession know that it is a safe treatment,[10] but we also appreciate how easily accidents can happen. This paper has presented the evidence for and against the IVD recommendations and discovered that the papers suggesting IVD is worthwhile carry more weight than those suggesting it is unnecessary. It is the author's belief that investing in IVD is worthwhile because protecting our patients must be a priority, particularly as treatments become increasingly complex and doses are escalated. In an ideal world, where departments are fully staffed and have endless money, there would be no excuse for not implementing IVD. In the real world, perhaps funding is better spent on developing new techniques that can drastically improve patients' outcomes. Many departments may have researched IVD methods and decided not to invest in technology that cannot verify dose in IMRT, IGRT and other modern radiotherapy techniques. When EPID IVD systems become available, that will be the time for departments to invest in IVD, thus improving the quality of radiotherapy they deliver to their patients.

References

1. Henk JM. A brief history of British radiotherapy. Int J Radiat Oncol Biol Phys 1996; 36:213–218.
2. What radiotherapy is. <http://www.cancerhelp.org.uk/about-cancer/treatment/radiotherapy/about/what-radiotherapy-is> Accessed 2 April 2010.
3. International Commission on Radiation Protection (ICRP). Prevention of accidents to patients undergoing radiation therapy. ICRP 86. Ann ICRP 2001; 30.

https://doi.org/10.1017/S1460396911000082 Published online by Cambridge University Press

4. Munro AJ. Hidden danger, obvious opportunity: error and risk in the management of cancer. Br J Radiol 2007; 80:955–966.
5. Morgan SA, Yarnold JR, Patterson D. The severity of late skin damage related to fraction size in women treated by radiotherapy after mastectomy. Radiother Oncol 1987; 8:315–319.
6. Goldner G, Zimmermann F, Feldmann H, Glocker S, Wachter-Gerstner N, Geinitz H, Becker G, Pötzi R, Wambersie A, Bamberg M, Molls M, Wachter S, Pötter R. 3-D conformal radiotherapy of localized prostate cancer: a subgroup analysis of rectoscopic findings prior to radiotherapy and acute/late rectal side effects. Radiother Oncol 2006; 78:36–40.
7. Department of Heath. *Reference Guide to Consent for Examination or Treatment*, 2nd edn. Department of Health: London, 2009.
8. Bomford CK, Kunkler IH. *Walter and Miller's Textbook of Radiotherapy: Radiation Physics, Therapy and Oncology*. Churchill Livingstone: London, UK, 2002.
9. Donaldson L. Annual Report of the Chief Medical Officer 2006. Department of Health: London, 2006.
10. The Royal College of Radiologists, Society and College of Radiographers, Institute of Physics and Engineering in Medicine, National Patient Safety Agency, British Institute of Radiology. Towards Safer Radiotherapy. The Royal College of Radiologists: London, 2008.
11. McKenzie A, Briggs G, Buchanan R, Harvey L, Iles A, Kirby M. Can we afford not to implement in-vivo dosimetry? Balancing costs and benefits of checking in radiotherapy. Br J Radiol 2008; 81:681–684.
12. Edwards CR, Hamer E, Mountford PJ, Moloney AJ. An update survey of UK . *in vivo* radiotherapy dosimetry practice. Br J Radiol 2007; 80:1011–1014.
13. Eddy A, Eddy D. In Cherry P, Duxbury A (eds), *Practical Radiotherapy Physics and Equipment*. Greenwich Medial Media: London, 1999.
14. van Elmpt W, McDermott L, Nijsten S, Wendling M, Lambin P, Mijnheer B. A literature review of electronic portal imaging for radiotherapy dosimetry. Radiother Oncol 2008; 88:289–309.
15. Huang G, Medlam G, Lee J, Billingsley S, Bissonnette JP, Ringash J, Kane G, Hodgson DC. Error in the delivery of radiation therapy: results of a quality assurance review. Int J Radiat Oncol Biol Phys 2005; 61:1590–1595.
16. BBC Frontline Scotland. Critical error; the Lisa Norris story. Broadcast 11 June 2007. <http://news.bbc.co.uk/1/hi/scotland/6731117.stm> Accessed 3 May 2010.
17. Scottish Executive Publications. Report into unintended overexposure of Lisa Norris at Beatson Oncology Centre, Glasgow in January 2006. Report of an investigation by the inspector appointed by the Scottish Ministers under Ionising Radiation (Medical Exposures) Regulations–IRMER. <http://www.scotland.gov.uk/Publications/2006/10/27084909/0> (2006). Accessed 2 February 2011.
18. Shafiq J, Barton M, Noble D, Lemer C, Donaldson LJ. An international review of patient safety measures in radiotherapy practice. Radiother Oncol 2009; 92:15–21.
19. Fiorino C, Corletto D, Mangili P, Broggi S, Bonini A, Cattaneo GM, Parisi R, Rosso A, Signorotto P, Villa E, Calandrino R. Quality assurance by systematic *in vivo* dosimetry: results on a large cohort of patients. Radiother Oncol 2000; 56:85–95.
20. Harrison R, Morgan A. *In vivo* dosimetry: hidden dangers? Br J Radiol 2007; 80:691–692.
21. Cozzi L, Fogliata A, Nicolini G. Pre-treatment verification of intensity modulated photon beams with films and electronic portal imaging–two years of clinical experience. Z Med Phys 2004; 14:239–250.
22. Vieira SC, Bolt RA, Dirkx ML, Visser AG, Heijmen BJ. Fast, daily linac verification for segmented IMRT using electronic portal imaging. Radiother Oncol 2006; 80:86–92.
23. Piermattei A, Fidanzio A, Stimato G, Azario L, Grimaldi L, D'Onofrio G, Cilla S, Balducci M, Gambacorta MA, Di Napoli N, Cellini N. *In vivo* dosimetry by an aSi-based EPID. Med Phys 2006; 33:4414–4422.
24. Williams MV, McKenzie A. Can we afford not to implement *In vivo* dosimetry? Br J Radiol 2008; 81:681–684.
25. MacKay RI, Williams PC. The cost effectiveness of *In vivo* dosimetry is not proven. Br J Radiol 2009; 82:265–266.
26. Wren K. *Social Influences*. Routledge: USA, 1999.
27. Malicki J, Litoborski M, Bogusz-Czerniewicz M, Swiezewski A. Cost-effectiveness of the modifications in the quality assurance system in radiotherapy in the example of in-vivo dosimetry. Phys Med 2009; 25:201–206.
28. NHSLA Factsheet 2: Financial information. <http://www.nhsla.com/home.htm> (2010). Accessed 2 February 2011.
29. Lanson JH, Essers M, Uiterwaal GJ *et al*. *In vivo* dosimetry: An essential part of a quality assurance programme of conformal radiotherapy. Radiother Oncol submitted.
30. The Royal College of Radiologists, Society and College of Radiographers, Institute of Physics and Engineering in Medicine, British Institute of Radiology. Implementing in-vivo dosimetry. The Royal College of Radiologists: London, 2008.