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Original Research Article

A multi-centre analysis of radiotherapy beam output measurement

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ABSTRACT

Background and purpose: Radiotherapy requires tight control of the delivered dose. This should include the variation in beam output as this may directly affect treatment outcomes. This work provides results from a multi-centre analysis of routine beam output measurements.

Materials and methods: A request for 6MV beam output data was submitted to all radiotherapy centres in the UK, covering the period January 2015–July 2015. An analysis of the received data was performed, grouping the data by manufacturer, machine age, and recording method to quantify any observed differences. Trends in beam output drift over time were assessed as well as inter-centre variability. Annual trends were calculated by linear extrapolation of the fitted data.

Results: Data was received from 204 treatment machines across 52 centres. Results were normally distributed with mean of 0.0% (percentage deviation from initial calibration) and a 0.8% standard deviation, with 98.1% of results within ± 2%. There were eight centres relying solely on paper records. Annual trends varied greatly between machines with a mean drift of +0.9%/year with 95th percentiles of +5.1%/year and −2.2%/year. For the machines of known age 25% were over ten years old, however there was no significant differences observed with machine age.

Conclusions: Machine beam output measurements were largely within ± 2% of 1.00 cGy/MU. Clear trends in measured output over time were seen, with some machines having large drifts which would result in additional burden to maintain within acceptable tolerances. This work may act as a baseline for future comparison of beam output measurements.

1. Introduction

Radiotherapy machines are calibrated to deliver a known dose under a set of standard conditions. During treatment, the dose delivered to the patient must be tightly controlled. There are Codes of Practice [1–7] which are provided by various standards laboratories which all centres should follow. These give details on implementing a traceable calibration chain to the primary standard, which in turn is inter-compared with others around the world [8]. Following the initial calibration, the beam output is monitored to ensure consistent and accurate dose delivery. This ongoing monitoring forms part of a larger quality assurance (QA) programme, however the frequency of testing is known to vary between different centres [9]. Often a 'consistency device' is used on a daily basis [10] with a measurement performed by a traceable ionisation chamber less frequently. Tolerances used for these beam output measurements can also vary between centres, with tolerances for daily measurements using a consistency device ranging between ± 1% and ± 5% [9]. Recommended tolerances for daily output constancy and monthly calibration checks are typically ± 5% and ± 2% respectively [10–12].

The variation in delivered dose will have a direct clinical impact on the patient and a number of factors contribute to the overall dose variation [13,14]. Treatment techniques have advanced such as with the introduction of Intensity Modulated Radiotherapy (IMRT) and now with the growing use of automated planning techniques, planning is becoming more consistent [15,16]. However, the variation in dose due to the allowable range of beam output has largely remained unchanged with many centres using a ± 2% tolerance on the allowable beam output [9]. Audit programmes are in place which assess the accuracy of the beam calibration. These audits include those as part of clinical trials, regional audits and national audits [17], with beam output audits commonplace worldwide [18,19]. The consistency of the implementation and maintenance of absolute beam calibrations has been shown to be either consistent or to improve over time [20]. However, no large

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study of the routine local beam output measurements across multiple centres has been conducted, and this variation from the initial calibration may have a similar significance in overall dose variation.

Previous work examining the variation in beam output data over time has focussed on an individual centres treatment machines [21,22], whereas this work aims to give a broad representation of the multi-centre variation in machine beam output measurements. The presence of trends over time, variation between measurement devices, and recording methods were investigated. Through tighter control of beam output, the variation in patient outcomes could be reduced. This work acts as a benchmark for the current variation in dose due to variations in beam output.

2. Materials and methods

2.1. Data collection and formatting

A request for data was sent by email to all UK radiotherapy centres through the regional audit network [23]. The data requested was for 6MV beam output data covering the 6 month period from January 2015 to June 2015. This time period was chosen as a balance between being a manageable dataset for centres to collate, and being representative of variations in measurements seen over time. Data requested included; treatment machine model, machine install date, measurement device, data recording method, and measured beam output. A quantitative statistical analysis of the data was performed to evaluate the variations which exist in measurement of beam output. Statistics including the mean output were calculated for each treatment machine allowing comparison of delivered dose across centres and within the same centre. The *Radiotherapy Services in England 2012* report [24] states that there were 265 linacs in use across 58 centres. Based on this we estimate there was approximately 300 linacs in operation at the time of data collection for this work.

For the purposes of this work, the data was collated and formatted so that beam output was represented as a percentage deviation from initial calibration. For example, a beam considered not to have changed from initial calibration would have an output of 0%, whereas one which delivers 2% greater dose relative to that at calibration would have a beam output of +2%. To remove outliers, a tolerance of ± 5% was used, as centres would generally not continue treatment if output deviated to this extent [9], and a majority of these values are actually erroneous results as stated by the centres during submission. In total 59 data points (0.22%) were removed from the dataset (53 of these were over 10% and were most often accompanied by repeat measurements which were within the normal range, thus indicating erroneous results), leaving a total of 24,501 measured beam outputs to be included in the analysis.

2.2. Data analysis

The centres were designated as *small*, *medium* or *large* based on the lower and upper quartiles of the total number of centres housing a particular number of treatment machines. This resulted in approximately even sized groups ensuring meaningful comparisons could be made. A small centre contained 2 or fewer, medium had 3 or 4, and a large centre had 5 or more machines. This resulted in 20 small, 13 medium and 19 large centres. For the purposes of this work satellite centres were treated separately from their parent centre. It was found that there was no significant difference observed between data from centres of differing size, and so no results split by centre size are presented. A breakdown of the distribution of centre size is given in the supplementary material S1.

It is known that the beam output will tend to drift over time, often at differing rates dependant on the age of the installed in-head ionisation chamber. The observed variation in beam output over the six month period was assessed for each treatment machine and results were linearly extrapolated to give the annual trend. The results have then been grouped by manufacturer and treatment machine age (in-head ionisation chamber age was generally not known for this dataset).

In many cases it was observed that a treatment machine or measurement device had been recalibrated which was clear from step changes present in the data (see Fig. 2 for an example), and so this calibration jump was removed to allow a more robust analysis of the trends over the data span of 6 months. The data was corrected by subtracting the magnitude of the identified step change from all subsequent data. Removal of this step change aims to remove this ambiguity within the data and give a truer representation of the overall drift in beam output. Where appropriate results were separated by treatment machine manufacturer to assess the differing technologies used by each. Results presented are from data which was normally distributed and so comparison was performed by means of a *t*-test where appropriate. When repeated t-tests were performed a Benferroni correction was used to adjust for multiple comparisons.

Data was received in a variety of formats including paper records (scanned or manually transcribed), database systems (in-house or commercial) and spreadsheets, with many centres using a mix of recording techniques. A common method was to transcribe paper records into an electronic system to allow trend visualisation and additional analysis. There were eight centres which solely relied upon paper records for beam output checks. A breakdown of the recording methods used for different sized centres is given within the supplementary material S2.

The oldest machine at the time of data collection (2015) was 16 years old (installed in 1999). The age of machines in the dataset is given in Supplementary material S3 giving a breakdown by manufacturer. The optimal lifespan of treatment machines is generally considered to be 10 years [25,26] and so data was assessed to identify any variation with machine age.

Where data was supplied for both constancy device measurements and ionisation chamber measurements the mean output as measured by each of these devices has been compared for each machine.

3. Results

Data was received from 52 centres, and included 204 treatment machines. A breakdown by manufacturer is given in Table 1. The install date was provided for 187 treatment machines, 47 of which were older than 10 years. Detail of machine install year is given in supplementary material S3.

The data included 41 National Health Service (NHS) centres (190 treatment machines) and 11 privately funded radiotherapy centres (14 treatment machines). Measurement frequency varied between daily and monthly and most commonly results were recorded in a mix of paper based and electronic formats (a breakdown of recording method by with centre size is given in supplementary material 2).

A variety of constancy devices were reported in use, which range from those having a single ionisation chamber or diode, to those with

Table 1
Summary of fitted linear trends of beam output over time for each manufacturer after correction for calibrations. There was no statistically significant difference observed between manufacturers at the 95% level ($p > .05$).

Manufacturer	Number of machines	Mean trend (%/year)	Median trend (%/year)	Trend standard deviation (%/year)
Varian	96	1.22	0.78	2.27
Elekta	92	0.71	0.44	2.03
Siemens	12	−0.06	0.98	3.31
Tomotherapy	3	0.72	−0.26	2.11
CyberKnife	1	−1.06	−1.06	N/A
All	204	0.89	0.56	2.27

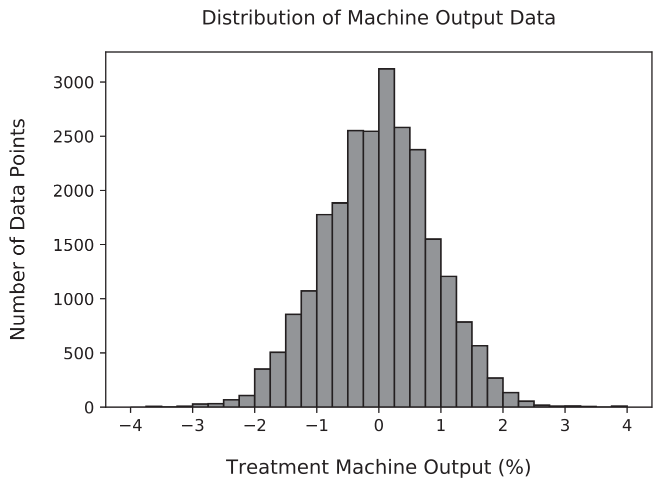

Fig. 1. Distribution of measured machine output. Data has a mean of 0.0%, with a standard deviation of 0.8%. There are 75.7% of measurements within ± 1%.

arrays of measurement points which are also capable of measuring additional aspects of the beam such as energy, symmetry and flatness. There are now also implementations using the treatment machines imaging panel which allow checks of multiple aspects of the beam and these are also included within the dataset.

The measurements were normally distributed with a mean of 0.0% and a standard deviation of 0.8%. This distribution of measured machine output is given in Fig. 1.

The number of beam output measurements exceeding a ± 1% was 5947 (24.3%) with 47 (1.9%) exceeding ± 2% and 45 (0.2%) exceeding ± 3%.

3.1. Trends in beam output

Within this 6 month data set 35 treatment machines were seen to have a single calibration and 7 treatment machines had two calibrations performed during this period. Fig. 2 shows a typical set of output measurements from a single machine with daily and monthly measurements taken using different measurement devices. In this case the daily and monthly measurements are considered well matched with less than 0.5% difference in mean results between the measurement devices. In Fig. 2 key aspects of beam output measurements are observed. A period of upward trend between March 2015 and June 2015 is seen

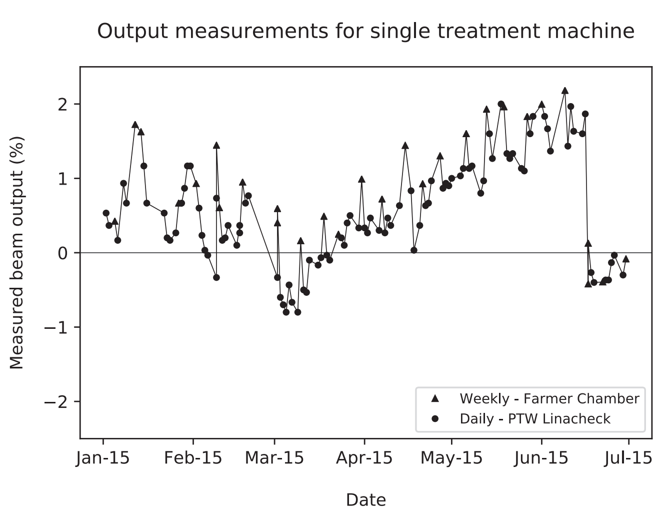

Fig. 2. Typical set of beam output data showing weekly Farmer chamber and daily Linacheck measurements for a single linac. This dataset includes a period of upward trend from March 2015 to June 2015 followed by a calibration.

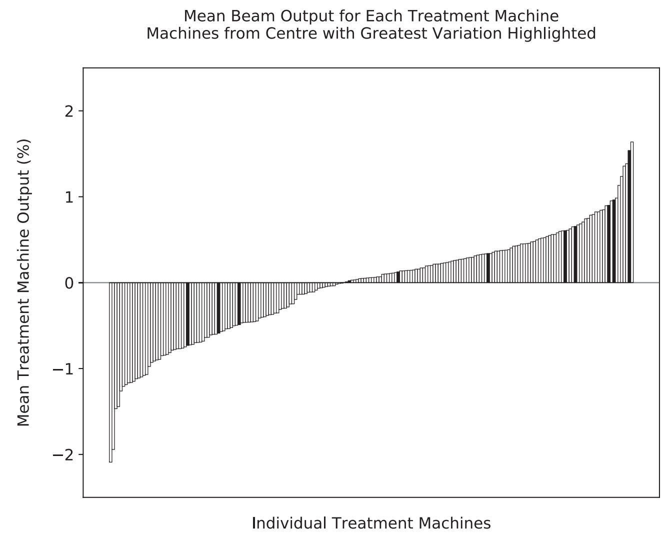

Fig. 3. Plot showing the mean output from each treatment machine over the data collection period plotted in order of mean beam output. The machines from the centre with the greatest intra-centre variation are highlighted and have a range of 2.2% (range 0.7–1.5%). These machines showed no statistically significant difference between measurement devices used ($p > .05$) and in the case of the highlighted machine two separate types of constancy device were in use.

followed by a calibration.

The overall observed trend in beam output drift for all treatment machines was +0.9%/year. The 95th percentile was +5.1% and 5th percentile was −2.2% indicating the large inter treatment machine variation possible.

No significant difference was seen at the 95% level ($p > .05$) between the beam output trends of different manufacturers. A summary for each manufacturer is presented in Table 1.

3.2. Mean machine output

The mean output for individual machines ranged between a maximum of +1.6% and a minimum of −2.1% with an overall mean of 0.0%. The 5th and 95th percentiles were −1.1% and +0.9% respectively. Within a single centre the greatest difference in mean output was 2.2% (range −0.7% to +1.5%). The values for this centre are highlighted in Fig. 3 which shows the mean output for each machine. In the case of the highlighted centre in Fig. 3 two different types of constancy device were used across the machines, however there was no statistically significant difference between measurements made with the devices when compared with ionisation chamber measurements. An intra-centre variation of > 2% was observed for 4 of the 52 centres (7.6%), and a variation of > 1% for 23 centres (44.2%). The mean intra-centre variation was 0.87%.

3.3. Variation between measurement devices

Of the 204 machines, 99 provided data for measurements taken with ionisation chambers (used weekly or monthly) and with a separate consistency device (used daily).

On five machines (not all within the same centre) the mean difference in measured output between the consistency device and ionisation chamber measurements was > 1% and 28 exceeded 0.5%. All but one of these was deemed statistically significant ($p > .05$).

There has been no observed statistically significant difference of measurement consistency between different measurement devices across the machines.

4. Discussion

This work contains the first analysis of local beam output measurements from multiple centres which is in contrast to previous studies based within a single centre [21,27,28]. The mean output of each machine within a centre was assessed to give an indication of the overall variation in delivered dose due to beam output to patients within that centre (Section 3.2). This indicated differences in delivered dose of over 2% are possible due to beam output alone. The variation of measurements taken with different devices on the same machines was examined. While most had good agreement, there were some which had differences in the mean measured value of over 1% in which case it would be recommended to recalibrate the constancy device to better match the ionisation chamber measurements if possible.

Obtaining the data from the centres was often troublesome, either due to resource implications, or due to systems not being able to export the required data. With a continual drive to modernise services, to introduce collaborative networks between centres and move records to an electronic format this study has highlighted the importance of the initial stages of implementing an electronic QA system including full commissioning of all documented features including access to data at a later date.

It is known that measurement practice varies between centres [9], however in one case a centre stated that when taking beam output measurements during their morning run-ups they had an asymmetric tolerance of −2% to +1%. The reason given was that the beam output would increase through the day, and so when their high dose treatments were delivered (usually in the afternoon) the beam output would be closer to the calibration value (with the effective tolerance shifting to ± 1.5%). This highlights the variation in practice between centres.

Comparing with national recommendations of monthly beam output checks to be within ± 2% [10] there was only 1.9% of all individual measurements outside of this range within this dataset. A single machine had a mean measured output outside of this range over the entire 6 month data period at −2.1% which was perhaps surprising considering the national recommendations are to be within ± 2% for monthly checks.

There is potential for large intra-centre variation on dose received by the patient depending only on the treatment machine they are assigned to. The largest range within a single centre was 2.2% (see Fig. 3) which is potentially a significant difference, dependant on patient dose response.

Whilst many centres were moving towards electronic data storage methods, eight centres relied fully upon paper records, and so may not be able to readily quantitatively assess trends within datasets. It is noted that of the 20 centres with two or fewer treatment machines, only one of these centres relied solely on paper records for recording beam output measurements (see supplementary material 2 for more detail on recording methods). This may be because of the increased flexibility of small centres to adapt practices and conversely the larger initial burden of transferring between record keeping systems at larger centres. There was no significant difference in the output measurements between centres which relied either solely on paper or electronic records, however comments were made by clinical staff that historic electronic records are often easier to access and collate, and when requesting the data for this study, those with paper records were more reluctant to provide them due to the potential time burden.

The data received from each centre varied; they provided either all measurements, or only a subset (such as daily, monthly or weekly) of these. Differences in measurement device would result in differing uncertainties on each individual set of data and it is acknowledged that this may affect comparisons between machines; however this has not been quantified within this work. A comparison of measurements taken with different devices on each machine indicated differences of over 1% on some machines; however tolerances for this comparison would be determined locally and is dependent on a number of factors including the device used and the frequency of alternative measurement techniques. It has also been noted that the mean of measurements made with a Farmer chamber was greater than those made with consistency devices on two thirds of machines and this warrants further investigation.

Manufacturers have slightly different technology within their treatment machines, and so there is potential for different rates of change in beam output. For instance, Varian uses a sealed ionisation chamber whereas the chamber for Elekta is unsealed. It has been noted through communication with clinical staff that the beam output of a Varian linac will tend to mirror a change in atmospheric pressure indicating chambers are not completely sealed units. Excluding CyberKnife (which only had a single machine within the dataset) all manufacturers showed both positive and negative trends in beam output drift within their treatment machines. There was no significant difference ($p > .05$) in the trends in beam output observed between machines from different manufacturers within this dataset.

A previous study of three Varian linacs by Hossain [21] concluded an annual trend in output of 2–4%, and this compares reasonably with that found for the Varian machines in this study of 1.2% (± 2.2%)/year (1 SD). A study by Grattan [27] indicated that the variation may be model specific and may vary with age. We found no statistically significant differences with machine age however longer term data would provide a more robust insight. As not all details of calibrations of machines and devices were known in this dataset it was not possible to apply reliable corrections to constancy device measurements and so the data was used as it was supplied. It is however felt that the large volume of data will reduce any influence of mis-calibrated measurement devices to some extent. If a similar study was repeated, it would be beneficial to obtain details of both machine and device calibrations.

As treatment techniques become more precise, particularly with the increased use of intensity modulated techniques [29] and greater standardisation, this reduction in planned dose differences between patients due to increased consistency between treatment plans (which may further reduce with the introduction of automated planning techniques [15,30]) will result in dose variation due to the beam output becoming of greater overall significance.

There is potential for patients treated on different machines to experience differing treatment outcomes if the beam output is not maintained within strict limits throughout the duration of their treatment. This dataset highlights the possible differences in beam output between machines over a given time period. This variation directly relates to delivered dose and so also to patient outcomes [31], further highlighting the importance of routine monitoring and maintenance. There was no major cause for concern when examining the machines included within this study, and overall they are all closely matched; further studies could be warranted to investigate the potential clinical impact of reducing variation in beam output and influence of use of different measurement devices.

This work presented the range of practices in measurement variation across different centres and gives quantitative results for the variation in beam output on different machines within a single centre. The variation over time of beam output on each machine was quantified, and again a large possible variation between machines is observed. This work may act as a baseline for further work such as investigating the impact of these variations on the development of QC schedules, and on clinical outcomes. Whilst considered a routine measurement, control of beam output should remain a high priority to ensure the high precision and accuracy required in radiotherapy is met.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.phro.2017.12.001.

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