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SHORT COMMUNICATION

Image guidance protocols: balancing imaging parameters against scan time

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Objective: Optimisation of imaging protocols is essential to maximise the use of image-guided radiotherapy. This article evaluates the time for daily online imaging with TomoTherapy® (Accuray®, Sunnyvale, CA), separating mechanical scan acquisition from radiographer-led image matching, to estimate the time required for a clinical research study (VoxTox).

Methods: Over 5 years, 18533 treatments were recorded for 3 tumour sites of interest (prostate, head and neck and central nervous system). Data were collected for scan length, number of CT slices, slice thickness, scan acquisition time and image matching time.

Results: The proportion of coarse thickness scans increased over time, with a move of making coarse scans as the default. There was a strong correlation between

scan time and scan length. Scan acquisition requires 40s of processing time. For coarse scans, each additional centimetre requires 8s for acquisition. Image matching takes approximately 1.5 times as long, so each additional centimetre needs 20s extra in total. Modest changes to the imaging protocol have minimal impact over the course of the day.

Conclusion: This work quantified the effect of changes to clinical protocols required for research. The results have been found to be reassuring in the busy National Institutes of Health department.

Advances in knowledge: This novel method of data collection and analysis provides evidence of the minimal impact of research on clinical turnover. Whilst the data relate specifically to TomoTherapy, some aspects may apply to other platforms in the future.

The success of radiotherapy in achieving tumour control and cure depends principally on the total radiation dose, which is limited by the tolerance of the surrounding normal tissues. Technical developments such as intensity-modulated radiotherapy (IMRT) have facilitated dose escalation and toxicity reduction by more effectively conforming the high dose volume to the shape of the target [1–7]. This is particularly true of tumour sites with complex irregular shapes.

A key concept in IMRT is the development of treatment plans with steep dose gradients, adjacent to dose-limiting critical normal tissue structures. This provides the opportunity to dose escalate the tumour and reduce dose to the surrounding tissue, but only if the dose can be delivered accurately. Thus, the full benefits from IMRT can be obtained only with the use of accurate targeting using

image-guided radiotherapy (IGRT), although it is not yet being used with all IMRT cases [8]. Online IGRT allows correction of both systematic (treatment preparation) and random (treatment delivery) errors [9,10], so that targeting can be more accurate [10], providing greater security of target coverage and reducing the dose to surrounding normal tissues [11,12]. The combination of IG-IMRT allows treatments previously considered impossible [7]. It may also allow planning target volume (PTV) margin reduction, although caution is required [13].

Optimisation of imaging protocols is essential to provide access to IGRT for as many patients as possible. This includes the frequency of imaging, the quality of imaging, the specific purpose for which it is required and the time taken to image and correct the patient's position. This article evaluates the time required for daily online imaging with

TomoTherapy® (Accuray®, Sunnyvale, CA), separating the time components for mechanical scan acquisition and image registration. Information was collected for different scan slice thicknesses and scan lengths. This work was prompted by the need to define how much additional machine time would be required for changes in the imaging protocols for head and neck and prostate patients in our VoxTox research study [14]. These data may provide benchmarking data for the time required to undertake integrated online image guidance with positional correction for centres using TomoTherapy and could be adapted for centres using other treatment platforms.

METHODS AND MATERIALS

Approximately 440 new cases are treated per annum across our 2 TomoTherapy units, with about 45% prostate cancer, 24% head and neck cancer (HNC), 8% central nervous system (CNS) tumours and 23% other cases [7,15]. All patients are imaged daily.

Between 2007 and 2012, a total of 25 129 treatments were recorded on the timing database. The sequential steps in the treatment were recorded as follows: patient enters the maze, starts scan, starts registration, ends registration, treatment beam on, treatment beam off and, finally, patient exits the maze. Initially, timing was recorded manually, but in 2008, a bespoke database was written, such that timings were recorded semi-automatically with a click of the mouse for each step [15]. Additional data were collected relating to the image guidance scanning, including a number of CT slices, and slice thickness. The timing database allows the different components of image guidance to be examined separately. Specifically, it is possible to distinguish the scan acquisition time from the image registration time.

Scan acquisition time refers to imaging once the patient has been set up and the radiographers have left the maze. It is defined as the time between the radiographers preparing to acquire the scan and the completion of processing ready for image registration. Image registration time is defined as the time from which the acquired image is ready for registration to the acceptance of the necessary geometric couch shift. Variation can occur because this is only a semi-automatic data collection method. Data were analysed by patient diagnosis, year of acquisition, scan length and slice thickness.

The TomoTherapy Hi Art® system can be set up to produce CT slices with a nominal equivalent thickness of 2, 4 or 6 mm, representing “fine”, “normal” and “coarse” settings, respectively, by changing the pitch of the machine. These are illustrated in Figure 1. The treatment radiographers determine the scan settings based on departmental protocols. A combination of different settings over the patient’s treatment course may occur depending on the need. The spatial resolution of the images is finer with smaller slice thicknesses, particularly in the longitudinal direction. By contrast, imaging dose is less and acquisition speed is faster with larger slice thicknesses [15].

From the 25 129 treatments recorded, 805 had fine resolution, 1917 had normal and 22 407 had coarse scans. From this, data were identified for head and neck (6004 scans), prostate (including

pelvic nodes; 11 197 scans) and CNS (1332 scans), totalling 18 533 scans. Data analysis was completed “blind” to the results of the calculated times from the machine performance characteristics.

Direct calculation of time for additional slices and different slice thickness

An increase in the volume being imaged and a reduction in slice thickness result in an increase in the number of slices acquired and therefore an increase in imaging time. The time taken to acquire an additional slice is 5 s, a figure defined by the machine characteristics [16]. From this, the additional time corresponding to an increase of 1 cm in the length imaged was calculated. This represents a method for independent corroboration of the timing measurements.

Image matching

Image matching is radiographer-led. Details of our approach has been described previously [15]. Briefly, match structures are pre-agreed for each patient, with priority given to the primary site. Image matching depends on interfaces between fat and soft tissues and between soft tissue and bone. Initially, a rapid automated match is undertaken, measuring discrepancies with 6 degrees of freedom (6 df), using the automated “bone and soft tissue” protocol. If gross errors are detected, the patient is repositioned on the couch and rescanned. In practice, this is rare (0.3%) [15]. Then, automated matching is repeated with 4 df, for translational directions plus roll, which can be easily corrected using this machine. This matching is then manually refined to optimise the match. Action levels for positional correction are set at 1 mm for translations and 1° for roll.

Statistical analysis

For analysis, the timings of image guidance were divided into components for scan acquisition and for image matching. Correlations between scan time and scan length and between image registration time and scan length (expanding on data from Dean et al [17]) for different slice thicknesses were assessed for a linear correlation. The scan acquisition time and registration time are dependent on the variables of scan length and slice thickness. Both can be expressed by a linear correlation, where the gradient is dependent on slice thickness.

From this, the coefficient of determination R^2 can be calculated, expressing the proportion of the dependent time parameter (y) explained by the primary scan length parameter (x), where R^2 is close to 1, y is totally dependent on x ; as it reduces, the dependence of y on x falls, and other contributing factors need to be considered.

RESULTS

Over time, the proportion of coarse thickness scans has increased, so now almost all scans are done with this setting (Figure 2). Finer slices are reserved typically for CNS cases such as vestibular schwannoma and pituitary adenoma requiring the highest precision in longitudinal positioning.

Year-on-year, the scan length for HNCs and CNS has remained relatively constant. For HNC, this is because of the importance of positioning the spine and spinal cord in relation to the steep

Figure 1. Images from a kilovoltage CT scan [Toshiba Aquilion LB® (Toshiba Medical Systems® Europe B.V., Zoetermeer, Netherlands)] and megavoltage CT scans [TomoTherapy® (Accuray®, Sunnyvale, CA)] for the same patient: (1) kilovoltage CT performed for the purpose of radiotherapy planning [(a) axial, (b) sagittal and (c) coronal planes]; (2) megavoltage CT (MVCT) for image guidance acquired using the fine setting [(a) axial, (b) sagittal and (c) coronal planes]; (3) MVCT for image guidance acquired using the normal setting [(a) axial, (b) sagittal and (c) coronal planes]; (4) MVCT for image guidance acquired using the coarse setting [(a) axial, (b) sagittal and (c) coronal planes]. A, anterior; F, feet; H, head; L, left; P, posterior; R, right.

dose gradients delivered by IMRT. Conversely, prostate scans have reduced in length from an average of 12.8 cm in 2008 to 7.2 cm in 2012. This is the result of reflective service evaluation, staff training and efforts to minimise the imaging radiation dose.

The individual components of image acquisition, which is a purely mechanical process, and image matching, which is predominantly a human activity, were considered separately. These are shown, together with the totals, in Table 1.

Scan acquisition timing

Using the machine performance characteristics, the additional scanning time required per additional centimetre scanned is calculated to be 8.3 s for 6 mm of reconstruction spacing (coarse), 12.5 s for 4 mm (normal) and 25 s for the 2 mm (fine) setting. The equivalent times for each additional centimetre are shown in Table 2. These calculations are in excellent agreement with the

estimates from the machine timing data (18 533 scans) since the introduction of semi-automated timing methods [15] for all 3 CT scanning slice thickness settings (Table 2) and endorse the validity of the radiographers' timing data. In theory, compared with a fine (2 mm) scan, a normal (4 mm) scan is expected to take half as long and a coarse (6 mm) scan to take a third as long, and measured times were consistent with this (Table 2).

There is a strong correlation between scan time and scan length, with $R^2=0.80$ for fine, 0.74 for normal and 0.54 for coarse scans (Figure 3). The relatively high R^2 values also suggest internal validity in the scan time data set. For all scan thicknesses, the intersection of the linear regression line with the y axis is around 40 s, regardless of the scan length. This additional time accounts for couch travel into the machine and for computer processing both at the start and at the end of the scan acquisition. The formulae shown in Figure 3 can be used to calculate the time required to scan

Figure 2. Percentage of 25 129 scans done with 3 different thicknesses, over time. Note the change to use of coarse scans for almost all cases. From 2010, with 2 machines, 7000–7500 scans are being performed annually.

different lengths of a target. The beam on time can be calculated from the length of each scan, as a one-slice acquisition has a 21 s beam-on time, with each additional slice adding 5 s to the total. Analysis of the data reveals that 4.0% of the recorded scan acquisition times are less than the associated calculated beam-on time. This variance could be owing to a delay in starting the clock at the commencement of scan acquisition, an early anticipation of the end or the incorrect recording of the scan length, which is recorded manually. These values have not been removed from the analysis.

Image matching timing

Image registration took between 1.3 and 1.8 times longer than scan acquisition itself. For coarse scans, for all sites, registration was 1.5 times longer (Table 1). The correlation between scan length and scan registration time is weak, with $R^2 < 0.2$ for all slice thicknesses. This would indicate that additional external factors affect registration times, perhaps including radiographer's

experience [18], and time pressure on the treatment unit and staff. Nevertheless, the average match time of 1.5 times the scan acquisition time provides a useful usable figure estimating the effect of changes in imaging protocol. Thus, an increase of 1 cm in scan length using the coarse setting takes 8.3 s longer for scan acquisition and 12.5 s extra for image matching.

Slice thickness also had an impact on registration time because of the increased number of slices produced within a set distance as the slice thickness decreases (Table 1). Information from the (three tumour sites) VoxTox population together showed that mean registration times per slice were 7.8 s per slice for fine slices, 11.2 s for normal and 12.5 s for coarse.

Estimating the time impact of lengthening scans

The impact of the acquisition time of an extended scan is exclusively TomoTherapy-related, since the time taken is

Table 1. Scan acquisition and image matching times for the average scan length of prostate, head and neck and central nervous system (CNS) in patients for different settings of slice thickness

Site	Average scan length (cm)	Process	Scan acquisition and matching time (min)		
			Scan slice thickness		
			Fine	Normal	Coarse
Prostate	5.9	Acquire	3.1	1.9	1.5
		Match	5.5	3.5	2.3
		Total	8.6	5.3	3.8
Prostate and pelvis	12.2	Acquire	5.8	3.1	2.4
		Match	7.6	4.4	3.5
		Total	13.4	7.5	5.9
Head and neck	10.3	Acquire	5.0	2.7	2.1
		Match	7.0	4.1	3.1
		Total	12.0	6.8	5.3
CNS	5.9	Acquire	3.1	1.9	1.5
		Match	5.5	3.5	2.3
		Total	8.6	5.3	3.8

Table 2. Comparison of time required for *extra* scan length for different slice thicknesses, using direct calculation based on the machine characteristics, vs estimates from treatment machine records (18 533 scans)

Method	Extra scan length (cm)	Additional scan time (s)		
		Scan slice thickness		
		Fine	Normal	Coarse
Direct calculation	1.0	25.0	12.5	8.3
Estimates from machine timing data	1.0	25.1	11.6	8.0

Note the close agreement between scans.

dependant on the length of the scanned volume and does not relate to other platforms using cone beam CT technology. However, TomoTherapy is unconstrained by set scan lengths. It is therefore possible to use short scan lengths, or much longer scan lengths, according to clinical need.

The results from this evaluation allowed the calculation of the impact on the department from a modification of the imaging protocol for clinical studies. Firstly, it is important to consider the number of patients treated per day on a unit and what percentage might be recruited to a clinical study. Within this worked example, about 70 patients per day are treated across our two TomoTherapy units and, for this calculation, we assumed that 24% have HNC and 45% prostate cancer and there would be an 80% recruitment rate to the clinical study [19].

To fully image both parotid glands in the HNC study patients for offline processing, we estimated that scans would need to be lengthened cranially by a *maximum* of 2 cm in approximately 80%

of the cases, the other 20% having tumours situated more cranially and, therefore, having the entire parotids scanned routinely. A 2 cm increase in scanning length would require an additional 16 s of scanning time per patient per day using the coarse setting. Assuming 11 patients on treatment at any one time, this would lead to an increase of 2.9 min or less per day across both machines, or just less than 1.5 min per day on each machine.

Although, in principle, it would also take approximately 24 s extra per scan for matching, in this study, the additional imaged length would not strictly be required for the image guidance positioning, so registration would not be required. This additional time can therefore be excluded.

For prostate patients, a small substudy is planned where every other scan is done with the 4 mm normal slice spacing, rather than the standard 6 mm coarse slices. This increases the image acquisition time by 22 s on “normal” scan days (Table 1), and image matching takes an extra 68 s, giving a total increase of 90 s.

Figure 3. Scan time vs scan length for the three anatomical site (VoxTox study) series, broken down by scan slice thickness (semi-automated recording, from November 2008 onwards, 18 533 scans).

Assuming that 5 patients per day are imaged in the substudy, rather than the 27 or 28 patients typically on treatment, and that only half of these have normal scans on any given day, the total increase in time for the whole day over both machines averages 3.75 min, which is less than 2 min per machine.

The results show that, taken together, these two protocol changes may increase the total time per machine over the whole day by up to 3.3 min.

DISCUSSION

Many institutional departments in the UK have heavy clinical demand for modern techniques such as IG-IMRT. The 2007 National Radiotherapy Advisory Group report highlighted these service pressures and the need to continue to develop the service to provide better patient care [20]. The expansion of IG-IMRT is a part of this development [21–23]. Tensions often exist between developing a clinical service with the highest quality capabilities, maintaining a routine service and performing clinical research.

Understanding the practical aspects of image guidance protocols, and especially the time required, is an important part of the implementation of change. In this study, we have sought to extend our previous report [15] by breaking down the IGRT process into its two main components, to assess the effect of a clinical research protocol on patient throughput.

Little information exists in the literature describing the practical impact of variations in protocol when imaging using TomoTherapy. The majority discusses beam characteristics, physics profiling or case studies [24]. Timing data is typically divided into just three components: verification time, treatment time and general set-up. Sterzing et al [25,26] discussed the overall table time for patients treated using TomoTherapy. They found that the average overall treatment time of 24.8 min consisted of 5.1 min of set-up and other tasks, 9 min for IGRT, and 10.7 min treatment time. This is significantly longer than our average time in the room (maze entrance to maze exit) of 18.6 min [15,27]. Their contribution from image guidance is also longer than it is from our experience. These differences may relate in part to case mix and to clinical demands. For prostate patients, Ramsey et al [28] used fine or normal scan thickness and found that the mean time from the start of imaging to the beginning of treatment delivery was 7.1 min (range: 6.2–8.5 min). This included positional correction as well as scanning and image matching and is consistent with our data.

Korreman et al [24] provided a fascinating comparison of image guidance using different platforms, including results from questionnaires on two example cases. However, their TomoTherapy data do not include details of either scan length or CT slice thickness, making direct comparison with our data difficult. They assessed the time for image preparation, image acquisition and image reconstruction separately, but we present them together. For the head and neck case, their mean image preparation, acquisition and reconstruction time for a coarse scan was 5.5 min compared to our average of 2.1 min. Similarly, for the prostate case, the equivalent times were 5.1 vs 1.5 min. The

minimum in the range of reported times for the imaging are almost exactly the same as our own figures, suggesting that at least some centres must surely have been using coarse scan settings. Image matching was also reported to be slower in the study by Korreman et al [24] for both HNC (3.6 min) and prostate (2.7 min) cases than our coarse scan matching time (3.1 and 2.3 min, respectively) (Table 1). This is consistent with our findings that thinner CT slices, with more slices per data set, take longer to match.

Development of a coarse scanning protocol as standard

At the start of our TomoTherapy IG-IMRT programme, a multi-professional team was established to manage the clinical implementation [15,29]. This group met twice a week to review case selection, planning and the quality of image matching. Through this mechanism, confidence increased that imaging using the coarse CT slice setting was sufficient for IGRT in most patients. Although this results in poorer quality of images in the longitudinal direction, in our experience, it is nevertheless possible to achieve a reasonable match in most cases using visual interpolation (Figure 1). Where spatial resolution is not deemed appropriate by the radiographers, patients are scanned using a finer setting for subsequent fractions.

A formal evaluation of registration accuracy in a head phantom performed by Woodford et al [30] showed that normal slice megavoltage CTs are superior to coarse slices for the registration of shifts in the superior–inferior directions, with an improvement in residual error of about 0.4 mm. They also suggested that residual errors were slightly worse in the axial directions, which is different from both our experience and a formal measurement of imaging resolution, to which we contributed [31]. They did show that shortening the scan length did not affect residual errors, down to a length of 24 mm [30].

Three other important factors also need to be considered in decisions on slice thickness, namely imaging dose, patient throughput and PTV margins. In the UK, in particular, dose exposure from image guidance is considered relevant, even in the context of patients receiving doses of radiation for therapy. In general, centres endeavour to keep imaging doses as low as reasonably practicable. Decisions are required to achieve the optimum balance between dose and image quality. Ultimately, this is most appropriately based on clinical considerations. For TomoTherapy, unlike other platforms, dose can be reduced by increasing CT slice thickness. Use of coarse slice thickness requires a dose approximately three times lower than the use of fine thickness [15,31]. Although this may slightly compromise spatial resolution in the longitudinal direction, it does not significantly degrade axial resolution [31]. Korreman et al [24] also demonstrated that the finer the CT slice, the higher the radiation dose from the TomoTherapy imaging. However, their estimates of dose were smaller by about 2.2 times than our own estimates (0.4 vs 0.9 cGy for coarse scans) [15,24] and independent measurements [31]. For example, their estimate of dose from the normal thickness scan (0.7 cGy) approximates to our dose from a coarse scan (0.9 cGy). This may have an additional bearing on decisions regarding CT slice thickness.

At the start of our clinical implementation, we had access to only a single treatment machine for IG-IMRT. Therefore, consideration of minimising in-room time to maximise patient throughput was included in the optimisation of imaging and treatment parameters. A clear decision was also taken to keep PTV margins unchanged while we acquired experience. Thus, positional accuracy would improve and CTV coverage could be achieved with a high probability, even if longitudinal matching accuracy was potentially marginally poorer by the use of coarse rather than normal scans. The overall approach was presented to and formally approved by the Clinical Director.

Patients with short PTVs, such as pituitary tumours, are still scanned with fine slice CTs, and those with fiducial markers are typically scanned with normal slice thickness, to reduce longitudinal errors. Our imaging practice has evolved over time, based on our clinical experience. Decisions on IGRT scanning parameters require consideration of local needs and practices, which should be encouraged. For example, a new centre might wish to use the finest 2 mm CT slice reconstruction initially, until they were certain. This evolutionary approach indicates a responsible attitude to the use of radiation exposure for imaging.

Scanning and image registration time

The scatter in the timing data reduced substantially, and the correlation between scan time and scan length became much stronger, after the introduction of the semi-automated timing method [15]. This emphasises the need for automated systems for data collection, particularly in the high throughput environment. There was a strong correlation between scan time and scan length, and average times were essentially the same as times calculated from the machine characteristics. The timings were also consistent for different scan slice thickness. Some level of measurement error is inevitable in a very large data set collected in a clinical environment, but the relatively low frequency of scan acquisition times that were less than the associated beam-on time builds confidence in the robustness of the data set as a whole. The large size of the data set means that such errors will not affect our qualitative conclusions.

The data demonstrate a “dead time” of around 40 s (Figure 3), necessary for couch travel back into the machine and for computer processing. This “dead time” is similar to the figure given by Korreman et al [24] as “preparation time” and is comparable to other imaging modalities discussed by them. Reduction in this time would enhance the throughput. For example, halving of this figure would save around 11.7 min in a working day, which for two machines amounts to one additional patient (mean in-room time of 18.6 min) [15]. Reducing this time represents a target for the manufacturer, which would increase access to IG-IMRT, albeit modestly.

The scatter in the data of image registration times *vs* scan length was much larger than for scan acquisition times, reflected in the low value of R^2 . This almost certainly results from differences in the radiographers’ matching experience [18], the specifics of the case and time pressure on the treatment unit.

Image registration took 1.5 times longer than scanning itself for 6 mm scans (Table 1). This is a useful figure, which can be applied pragmatically to estimate the effects of changing scan length. There was a greater effect on time from the number of slices than the slice thickness. This almost certainly relates to the greater amount of information to appraise when more slices are scanned.

Estimating the time impact of lengthening scans

Changes to clinical protocols may become necessary for both clinical and research reasons. This evaluation allows a robust estimate of the effect of altering the IGRT protocol.

When using the coarse 6 mm slice thickness, each additional centimetre of scan length takes an extra 8 s for acquisition and just under 12 s for image matching, totalling to 20 s.

The work was initiated to quantify the effect of modest changes to the clinical protocols for our VoxTox study and, in particular, to reassure the department of a minimal effect on total patient throughput. Two changes were needed. The first is to ensure that the whole parotid gland is scanned to provide clinically valuable dose–volume histogram data for off-line radiobiological analysis. This should require less than 1.5 min per machine per day. Secondly, we are seeking to optimise the imaging for prostate patients. This study should take less than 2 min per machine per day. These results have been reassuring in the busy National Health Science department, which is committed to developing its service for patients through clinical research.

CONCLUSION

The results highlight some of the issues that are relevant when implementing or amending imaging protocols. The analysis provides evidence of the minimal impact that this clinical research will have on patient throughput. Whilst the data and formulae relate specifically to TomoTherapy, some aspects may apply to other platforms, when considering changes to imaging protocols. We plan to apply the same method of data collection and analysis to the use of cone beam CT imaging, which has become available recently in our department. Comparison with data from other departments and platforms would also be of interest.

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