Review article

Is tomotherapy the future of IMRT?

A W BEAVIS, PhD, BSc

Department of Medical Physics, Hull and East Yorkshire NHS Trust and Post Graduate Medical Institute, University of Hull and Princess Royal Hospital, Saltshouse Road, Kingston Upon Hull HU8 9HE, UK

Abstract. Intensity-modulated radiotherapy (IMRT) has become established in many clinics round the world and is, arguably, technically feasible in any facility. Serial tomotherapy contributed an extensive role in its introduction into the mainstream in the second half of the 1990s. In tomotherapy, literally “slice therapy”, highly conformal treatments are possible because of the advantages available within the treatment planning of the IMRT process. Currently the majority of clinics implementing IMRT are doing so using conventional clinical linear accelerators (Linacs) fitted with an integrated multileaf collimator (MLC). At this point in time we may wonder if there is any scope for further dramatic changes in this new technology. As we venture from IMRT initial implementation into image guided therapy it is clear that major changes in approach are still valid and needed. If, at each treatment fraction, we can ensure that treatments are delivered accurately by integration of volumetric imaging into on-line validation, then we can attempt higher levels of conformality. A new treatment machine, the helical tomotherapy system, is available that combines the benefits of tomotherapy with on-line volumetric imaging. In this article we will review this approach and explore its features.

Intensity-modulated radiotherapy (IMRT) [1] has been introduced [2–4] into a wide spectrum of clinics worldwide. It is clear that recently its adoption has accelerated due to the availability of commercial planning and delivery software from all the major treatment planning and Linac manufacturers. A full description of the development and milestones of this novel technique is given by Webb [5] and more recently in the first article in this series [6]. In order to develop the theme for this article, we briefly revisit some of these points with some alternative reflections.

The popular introduction of IMRT started in the mid 1990s when the NOMOS Corporation (Swickley, Pennsylvania, USA) introduced the PEACOCK system [7, 8], this comprised of the MIMiC, a tertiary “bolt-on” multileaf collimator (MLC), and a dedicated inverse treatment planning system. The treatment delivered by this system is described as serial tomotherapy, since it is delivered by a number of discrete arcs or indexed arcs of finite width, between which the treatment couch is moved longitudinally [9, 10]. The first patient [8] was treated in 1994 and until around the turn of the century most patients who received IMRT in the world were treated on this system.

There is no doubt that the pioneering work of the NOMOS company and their customers hastened the transition of IMRT from being unique to the hospitals supported by academic groups, into the scope of any clinical department. It was reported at the American Association of Physicists in Medicine (AAPM) meeting in 2003 that as of July of that year 141 MIMiCs had been installed globally. Interest in the system was sustained with many sub-beams or segments. The first treatment of this type was given in 1996 [11]. Alongside the advantage of utilizing existing treatment equipment, the provision of appropriate software by the major treatment planning vendors has ensured this methodology is currently the more popular technique. It is reasonable to assume that in the coming years most patients will be treated using some derivation of this technique and vast experience will be gained by the community. Another article in this series [12] dealt with this treatment modality in depth and as such we will not explore it further.

The major criticism of contemporary IMRT is that we cannot be certain of the geometry (relative position and shape) of the tumour or organs at risk (OARs) at each treatment episode. Careful and exacting protocols are employed to attempt to localize these in the treatment plan, however this can only be considered as describing some average positioning on a snap shot of the anatomy at the time of acquisition. The development of new systems incorporates the common theme of image guided therapy (IGT). In IGT we seek to remove uncertainties in the knowledge of absolute position of the anatomy at the time of delivery, by acquiring volumetric images on the treatment device. There are several approaches currently being introduced including the combination of a conventional CT scanner and conventional Linac served by a common treatment couch [13, 14] and cone-beam kV CT [15] apparatus orthogonally mounted to the Linac treatment head.

At this time in the history of radiotherapy we might ask the question as to whether tomotherapy has completed its role in the development of IMRT. Recently, an exciting treatment machine (see Figure 1) was made commercially available (Tomotherapy Inc., Madison, Wisconsin, USA). The helical tomotherapy machine [16] differs from the approach adopted by NOMOS, in that the treatment is delivered in a spiral fashion (see Figure 2), removing the...
need to manually move the patient between arcs. Furthermore, with appropriate optimization/planning considerations it ensures that all treatment arcs are “feathered” by default and junctioning between “successful” arcs is no longer a concern. This treatment device is mounted upon a CT ring gantry and combines a dedicated IMRT delivery methodology with CT imaging capability. The first patient was treated using this machine in July 2003. As of April 2004 twelve of the helical tomotherapy machines have been installed in North America, and some 200 patients will have completed treatment by its end.

In this review we will present information about this new technology and debate some of the relevant issues.

Static beam delivery, arcs and tomotherapy

There are a handful of studies in the literature that seek to systematically compare delivery of conformal radiotherapy by static beam and arc based (such as tomotherapy) techniques. Verellen et al [17] conclude that for convex target geometries that whereas both modalities achieve treatment goals, dynamic (conformal) arcs fare better than static beam IMRT delivery with respect to treatment efficiency. As their name suggests the latter utilize arc based solutions, furthermore at each “arc position” the MLC leaf positions are adjusted to provide appropriate conformal (target) shielding. For more complicated (concave) treatment geometries the efficiency advantage was maintained though, as we might expect, OAR dose constraints were not upheld. In other words intensity modulation was required. In both cases serial tomotherapy plans provided good solutions though the treatment efficiency was compromised because of the high number of monitor units required. Pirzkall [18] noted that rotational IMRT proved to have a slight advantage over fixed field IMRT. Philosophically, the interesting aspect we might draw from these statements is that the use of arc based therapy is useful in providing highly conformal treatments and the addition of intensity modulation simply adds to this basic advantage.

Of course, this concept has been previously investigated and indeed used clinically, though on a very small scale. Intensity-modulated arc therapy (IMAT) was proposed by Yu [19, 20]. Here, in addition to the conformal shaping of the MLCs during the arc, multiple arc passes are delivered in order to lay down more than a single intensity level. Arguably, widespread clinical adoption has been slowed by the fact that the treatment planning manufacturers have not yet provided solutions for this methodology.

MacKenzie and Robinson [21] added an interesting facet to this discussion, they describe a method for “Intensity modulated arc deliveries approximated by a large number of fixed gantry position sliding window dynamic multileaf collimator fields”. The premise that we should want to deliver “tomotherapy-like” distributions using conventional equipment is itself interesting.

IMRT optimization: static beam delivery vs serial and helical tomotherapy

A detailed discussion of the treatment planning or optimization process was given by Webb in this series [6], however let us briefly “recap” the salient points for what follows.

We start the optimization process by defining a set of treatment beam directions, whose beams-eye-view (BEV) projections cover the planning target volume (PTV), each of these are subdivided into a regular set of beamlets. The volume to be irradiated may, of course, include OARs and we wish to minimize the doses delivered to these structures. A set of rules or constraints are defined that govern the target or maximum doses that each structure should receive, various other control parameters such as relative importance factors are included to resolve paradoxical demands. Essentially, these rules describe the idealized dose distribution wanted for that patient, collectively they form a cost function which is used in the optimization process to describe how badly treatment goals are compromised. By trying many different combinations of beamlet weighting and changing them systematically the optimization routine strives to find a minimum value of
the cost function, resulting in a plan that is a close approximation to the ideal dose distribution wanted.

One of the issues that affects how successful the optimization process in the treatment planning of IMRT is the number of beamlets it can utilize. In mathematical terms we denote this as the degrees of freedom available to a particular method. We can easily appreciate this from our experience in conventional planning where the greater the number of beams used the more conformal we can make our plan. The advent of MLCs made this a very practical and widespread philosophy and the advent of computer controlled “auto-set up” functionality on the treatment machines introduced it into widespread practice. Taking a step further back in time we remember that in the pre-Linac era (non-conformal) arcs were introduced to enable more optimal treatment of deep-seated tumours and combat the restricted skin-sparing afforded by cobalt beams. The use of a large number of co-planar beams in contemporary conformal treatments basically constitute “first approximation” arcs.

In order to make some comparison between the potential of the static beam and tomotherapy methodologies we will develop a simple example. Let us consider a PTV that exists within a 10 cm by 10 cm by 10 cm volume, intruding into this volume is at least one OAR with, potentially, further OARs lying very close to the volume.

### Static beam delivery

For the static beam delivery we consider using a fixed number (N) of beam portals, typically 5 to 9, which are 10 cm by 10 cm (in the BEV plane). In general each of these can be divided into 1 cm by 1 cm beamlets, we note that some MLCs can define a better resolution, however we will not consider this to be a significant issue as we can apply the same argument when we develop the tomotherapy discussion which follows. So, each beam will have 100 beamlets and we will have $100 \times N$ possible beamlets with which to control the dose distribution laid down.

### Serial tomotherapy

For serial tomotherapy deliveries we consider using a fixed number of arcs. In theory the arcs can describe a full 360 degree circle with “treatment beams” at each degree, in practice it is more realistic to consider them to exist at discrete angles, let us choose 51 equispaced angles. The width of the fan-beam (in the transaxial plane) at each delivery angle will be governed by the PTV dimensions in a similar manner as described above. Again, if we assume a 1 cm by 1 cm resolution then for each delivery angle there will be an arc of 10 beamlets. Assuming that 10 arcs are required at this resolution to treat the PTV, then there will be 51 \times 100 possible beamlets the optimizer could use.

For a simple comparison a seven field equispaced static beam delivery will be able to utilize 700 beamlets and a tomotherapy delivery as described above will have 5100 available beamlets. The comparison is not as simple as stated, since many of the tomotherapy beamlets may become redundant. In selecting directions in static beam delivery, we may not have the most optimal set of beamlets, we can improve this somewhat by selecting directions based on experience, nevertheless even a few degrees of annular change can improve a resulting dose distribution. The point being that although many of the tomotherapy beamlets may be eventually redundant they are initially available to the optimization process and are discarded by it and not a priori. So, even if we conservatively consider over half to be redundant we still have a good illustration of the much greater degrees of freedom, or potential to create highly conformal distributions, that tomotherapy offers.

### Helical tomotherapy

For helical tomotherapy deliveries we have another parameter to include! As the treatment beam rotates about the gantry, the couch supporting the patient is translated through it. This can be parameterized by a quantity known as “pitch” as in spiral CT, where a pitch of 1.5 is typical, resulting in the patient being longitudinally translated 1.5 times the width of the imaging beam for each full rotation. However in the treatment scenario a pitch of less than unity is beneficial, typically values of 0.35 or 0.5 are used, in order to irradiate voxels with several gantry rotations or arcs. If we consider a single voxel of unit length and utilization of a pitch of $P/P(P>1)$ then it will receive dose from beamlets from any/all appropriate beam directions over $P$ arcs. If we consider the delivery from each arc to deliver one “intensity level” then the pitch control allows $P$ intensity levels to be laid down in our voxel of interest. Furthermore, bearing in mind that the voxel is translating through the gantry the position of the “edges” of those intensity levels are also altered and controllable. This latter effect can be thought of in the same way as the “step size” or spatial discretisation [22] of intensity profiles in leaf sequencing for fixed field IMRT beams. Treatments planned on this system use 51 equispaced beam directions per gantry rotation, if we assume a beam width of 1 cm and a helical pitch of 1/5, then we now have 25 500 beamlets available, i.e. the serial tomotherapy answer scaled by the pitch.

Again, this argument is very simple but effectively illustrates the issue at hand, the inclusion of the helical pitch increases the degree of freedom further than in the serial tomotherapy case and means that the optimizer potentially has tens of thousands of possible beamlets at its disposal. If we consider very difficult problems such as pelvic nodal irradiation [23] and certain lung treatments [24] then the potential of the helical tomotherapy approach becomes very clear. In these complex geometries we wish to conformally treat the “rind” of the lung whilst minimizing the dose to the lung itself.

### Delivery of the intensity-modulated beams

In most current commercial implementations, the optimization of the treatment is separate from any considerations as to its deliverability. In other words, as far as it can achieve, a perfect treatment is proposed by the optimizer, and if the idealized radiation/fluence profiles it needed to use could be delivered, then it would be achieved. Following the optimization the leaf sequencing algorithm divides [22] the ideal beams into a series of deliverable sub-beams or segments. Compromises, in
relation to the realization of the ideal treatment beam, are required because of physical constraints determined by the specific delivery system (typically the MLC) in use. This results in the perfect dose distribution not being achieved. Various investigators are considering the inclusion of these “deliverability constraints” into the optimization process itself [25–28] thereby only proposing beams (and therefore dose distributions) that are truly deliverable. This would benefit all IMRT delivery schemes and will certainly make its way into all commercial planning systems eventually.

**Helical tomotherapy system**

The helical tomotherapy device was conceived and developed by the research group headed by Mackie [29] at the University of Wisconsin, USA. Latterly a commercial product has been realised, and marketed, by a spin-out company Tomotherapy Inc., Madison, USA.

The machine was designed to be a purpose built IGT machine, to deliver highly modulated IMRT whilst also being able to verify the integrity of the delivery of such treatment. It is best described by the rather romantic reflection that it is the marriage of a treatment Linac with a CT scanner. A 6 MV Linear accelerator waveguide and a CT (MV) detector subsystem (see Figure 3) are mounted upon a rotating gantry assembly, they are provided with power via slip-ring technology which also allows the transmission of data. The capability for continuous rotation, coupled with translation of the patient through the gantry, allows helical treatment arcs in an identical fashion to that now familiar on helical or spiral diagnostic CT scanners.

**Gantry and beam-line**

The gantry has an access bore with a diameter of 85 cm. The device is a single energy X-ray machine, hence the target is fixed with respect to the beam-line. Since it is a dedicated IMRT delivery system there is no flattening filter, the role of the redundant filter can be achieved via intensity modulation if required. Its exclusion enables dose rates of over 8 Gy min$^{-1}$ at the centre of the bore.

Independent jaws, integrated with the primary collimation, form the fan-beam, both are manufactured from an alloy containing 95% tungsten. The “clam-shell” design of the jaws provides maximum shielding whilst maintaining compactness, the latter is important in the design of this machine where it is undesirable to have bulky components resident on the rotating gantry. The primary/secondary collimation has been designed to ensure any “head” leakage for IMRT deliveries is comparable with that obtained for conventional treatments. The jaws can be continuously moved and completely opened or closed to form a 5 cm wide fan beam; typical treatment beam widths are between 1 cm and 5 cm.

**MLC**

The system incorporates a binary MLC, this is very similar to that used by the serial tomotherapy MIMiC device. The binary reference indicates that in operation the leaves are either open or they block the beam, hence turning individual beamlets on or off. This approach requires very fast leaf transition times and this is achieved by using a compressed air system enabling them to close or open in approximately 20 ms. There is also some “latency” or lag time due to associated mechanical delays/response times, however these can be ignored in the delivery since they are allowed for in the implementation of a “direct aperture optimization” algorithm. As discussed in the optimization section this leads to deliverable beams and the achievement of the dose distributions assumed by the optimizer.

There are 64 interleaved leaves, each has a nominal width of 6.25 mm at the isocentre, thus providing a fan beam length of 40 cm. Again they are constructed from a (95%) tungsten alloy. The leaves have a tongue and groove design and are 10 cm thick, these characteristics lend to limiting transmission to approximately 0.5% “in-field” and 0.2% outside. Mackie et al [16] have presented a detailed description and justification for the choice of MLC leaf width. Shepard et al have shown [30] that whereas a 6 mm leaf is seen to provide better dose homogeneity and normal
tissue avoidance than a 10 mm leaf, no benefit is seen if the leaf width is reduced to 2 mm.

Recalling that the entire beam-line/collimation system is fixed to the gantry and rotates about the patient this provides an imaging field-of-view (FOV) of a 40 cm diameter. The treatment FOV is wider. Let us consider a PTV which is 41 cm wide at its widest aspect. There will be two directions from which the 40 cm wide beam cannot irradiate the entire PTV, other beam directions will (obliquely) irradiate the entire volume. Developing this argument further we estimate that a cylindrical PTV with diameter of up to 60 cm could be treated and with some degree of non-uniformity (due to increasing number of excluded beam directions) a diameter of 70 cm could be achieved.

Couch

The patient support couch is similar to that found on spiral CT scanners, though naturally it has a flat top. The patient is positioned on it with the aid of conventional localization devices which can be indexed to the treatment couch. Automatic couch motion in the vertically and longitudinal directions are possible to position the patient correctly within the gantry and accurate longitudinal movement allows the patient to the translated through the gantry whilst the gantry rotates to enable the helical treatment approach. Manual lateral translation is allowed. The available couch translation allows unrestricted treatment volume lengths for the large majority of deliveries. The maximum treatment length is 160 cm length for a single spiral with the couch at isocentre height. However it is dependent upon actual couch height, due to the “Cobra-action” of the raising mechanism. Upto this length, long volumes can be treated without the need to match or feather sets of treatment beams. It may be necessary to junction helical fields for tall patients undergoing whole body exposure or total body irradiation, this is possible.

In the discussion of the benefits that the helical tomotherapy delivery afforded the treatment planning/optimization process we touched upon the concept of pitch. The pitch ratio is that between the distance the couch travels during a gantry rotation to the fan beam width. Typically, in the treatment scenario we want to use a fractional pitch meaning that each voxel of the patient is irradiated multiple times before the beam “moves on”.

MV imaging

The helical tomotherapy machine has an integrated (MV) CT imaging capability. A conventional xenon ion chamber CT detector system is mounted on the gantry directly opposite to the beam-line. This offers two benefits for IGT: the obvious one being the acquisition of volumetric CT imaging of the patient at the time of treatment delivery. Secondly, during treatment the intensity of the photons that exit the patient can be collected and used in a back-projection computation to assess the dose distribution that is delivered to the patient.

The imaging beams are produced at a lower quality/energy (3.5 MV) than the treatment beams and the output of the guide is reduced. This results in the acquisition of volumetric images at very acceptable doses, typically between 0.5 cGy and 3 cGy, which are comparable with doses required to obtain planar images on contemporary MV electronic portal imaging devices (EPIDs). Though an “off-the-shelf” system, the detector used has an inherent co-incident design benefit that provides a quantum efficiency of approximately 25%, which is much greater than for EPIDs. The detectors have thin tungsten septa that separate the ionization chambers, a significant number of electrons released at photon scattering events in the septa are conducted into the gas chambers and detected. So, whereas the septa were included to reduce cross-talk “noise” between detectors for kV imaging, they result in an increase in efficiency for MV CT imaging.

The system is designed to produce imaging for verification purposes, hence the obtainable contrast should be of an appropriate standard. A nice demonstration of its capability has been shown by Ruchala et al [31]. In this work they use a familiar CT contrast-resolution phantom and demonstrate the ability to detect a 3% contrast object with dimension of approximately 3 cm. This indicates that the contrast difference between fat and muscle for structures of reasonable dimensions (for example, prostate) will be identifiable. Furthermore the same work demonstrates that for higher contrast differences (air to solid water) objects of 1.2 mm are able to be resolved. It is this authors anecdotal experience that in discussions with Radiologist colleagues the MV CTs are remarked to be “much better than early kV CT images”.

Though the CT imaging of the helical tomotherapy machine is not intended to be used to collect diagnostic images, it may have a useful role in the treatment planning of radiotherapy patients. Any experienced treatment planner can testify to the problem and annoyance introduced by metal artefacts in CT planning scans. The non-linearity of attenuation, introduced by the photoelectric effect, results in severe streaking aberrations are seen in the images. As seen in Figure 4 these artefacts are simply not present in the MV CT images because of the different physical processes contributing to the creation of the image. For patients with artificial hips or dental fillings proximal to the PTV a MV CT could be obtained and registered/fused with the standard planning CT. In this way it could be used in parallel to the latter similar to the way an MRI is now commonly used in routine planning. In cases where the kV CT is potentially “worthless” due to severe imaging artefacts we might consider the use of the MV CT alone as MRI has been used [32, 33] in the past.

System software: planning system

The final part of this section on the helical tomotherapy system is briefly concerned with the planning system and other software associated with the treatment machine itself. It should be apparent to the reader that the treatment philosophy and therefore the optimization problems faced during planning are quite unique. The machine is sold as part of a completely integrated package and includes a planning system. The computational overhead of optimizing tens of thousands of beamlets is very large. To overcome this a parallel processing architecture is utilized using a computer comprising of 32 processors. Furthermore the calculation is split into two parts: a precalculation; and the optimization stage. In the former the basic calculations describing the beamlets and their
interaction with the patient are computed, this can be done in background or batched to be performed “over-night” since the operator is not required to interact with the system during this phase. Once these data are computed the user controlled optimization is performed, this process is a variant on the optimization methodologies discussed elsewhere in this series [6] and as such warrants no further discussion here. Figure 5a shows illustrative screen shots from the software showing the dose distribution for an Oesophagus treatment and Figure 5b the dose-volume histogram (DVH) obtained.

**System software: registration/fusion software**

As the system is built around an image-guidance principle, registration and fusion software clearly plays an important part of the process. A mutual information algorithm is provided as part of the software system. It is used to register the MV CT data, acquired at the patient “set-up”, with the planning (kV) CT used in the design of the treatment plan. Any mismatch in the patients positioning in a longitudinal or vertical sense can be fed to the control system and the couch position is adjusted automatically. Any rotation of the patient in the transaxial plane can be corrected by altering the “start angle” of the rotational delivery. Currently, lateral offsets may be corrected by manually driving the couch top.

Once the data sets have been registered they may be fused for the user to inspect. Normal useful features in such software tools are available such as image integration using “checker-board” displays (see Figure 6) enabling an easy comparison of the two data sets.

**System software: dose reconstruction software**

Dose reconstruction is a “high-end” form of transit dosimetry, where photons exiting the patient are collected, their intensity measured and used to compute the dose delivered to the patient. In conventional transit dosimetry for IMRT a delivered intensity/dose map may be computed by imaging the intensity-modulated beam during treatment, this requires that the portal imaging system be extended and in place throughout the treatment. On the helical tomotherapy machine the CT detectors are always in the beam-line by default and so they can easily be used to detect the exiting photons. Assuming that a MVCT had been made for that fraction, or a representative data set exists, the process can be taken a step further. Given that the anatomy is known the measured photon intensities can be back-projected through the virtual patient and a volumetric dose distribution can be computed [34, 35]. Whereas a daily CT is not strictly necessary, the advantage of having a true anatomy representation for that treatment fraction is obvious. This process is very similar to the reconstruction of the CT images themselves.

**Image-guided therapy and the adaptive therapy process**

The helical tomotherapy was designed not just as a dedicated IMRT delivery system but as an IGT delivery system. IGT is the next logical step in the evolution of IMRT to realise highly conformal treatments, here on-line (volumetric) imaging is used in order to localize the targets and conformal avoidance structures at each treatment fraction. This leads to the question: what do we do when
we detect that the treatment geometry has changed? In standard conformal therapy we establish our volume delineation and safeguard against organ motion/distortion or set-up errors by applying margins to the treatment volumes. In IGT we have the opportunity to reduce these margins and consequently give higher target doses and make fewer compromises to lower normal tissue doses. If we decide to follow this course of action then it demands we have a strategy for adapting the progression of the treatments when deviations from that planned are detected. Figure 7 demonstrates the “adaptive therapy” process.

Whereas it does not require the treatment is given by helical tomotherapy, the advantages of using a fully integrated system is obvious; the “process map” illustrated in Figure 7 clearly demonstrates the central importance of having good imaging capability in the adaptive therapy chain. We have discussed already the advantage of making a volumetric scan of the patient prior to delivering the treatment. Whereas we can either correct or account for set-up errors in some manner, we are unable to correct organ distortion or displacement. However, the delivered dose distribution computed for each fraction and the accumulated dose from all fractions may be used to track how closely the treatment is following that planned.

Figure 5. (a) An oesophagus treatment, the isodose levels given in the key or in units of Gy. This treatment took 12 min 24 s to deliver. Courtesy of Dr D Cho of the Southeast Regional Cancer Centre in Tallahassee, Florida, USA. (b) The cumulative dose-volume histogram obtained for the treatment whose isodose distribution is shown in (a). The colours of the curves relate to the structures shown in the images.
Interventional steps could be taken at any stage and with any frequency, however we need bear in mind that any changes to IMRT delivery will need to go through the appropriate quality assurance (QA) validation before being used. Typically this involves pre-treatment measurements [12] of various descriptions using film or the EPID devices [36] integrated to conventional Linacs. Nevertheless, with integrated tools such as dose reconstruction there will be a point in the future when we (as a profession) are comfortable with aggressive correction schemes.

It is most likely that in the first instance a protocol that makes one correction for the last week of treatment would be deemed most appropriate. At this time we might actually consider this quite ambitious as (in general) a change in volume will result in a very different IMRT delivery and therefore necessitate the same checks as any new treatment. However, departments that have been using IMRT for some time no longer perform patient specific QA, but perform secondary or independent dose calculations in its place. They are satisfied, from 5 to 10 years experience, that the intensity modulation is delivered accurately and in the way the plan demanded.

Taken to an extreme the daily delivery may be adapted based on the MVCT anatomy presentation, though faster and more powerful computers would be required to make the necessary calculations, however these are always just around the corner! In fact this correction scheme may not be so outlandish: not only will we eventually become comfortable with the ability of the treatment machine to deliver what is demanded, but with an IGT machine we will be able to easily measure the dose exiting the patient using its imaging system. The planning system could compute the expected exit dose patterns and compare them in real time with those measured, if a significant deviation were detected then an interlock could be applied. Any minor deviations detected would be simply fed back into the "adaptation process" described in Figure 7. In other words we replace pre-treatment QA with during-delivery QA. Would this be accurate enough? Given that the anatomy presentation is "measured" before delivery of the treatment this comparison is more likely to be relevant than in the contemporary setting. The latter suffers from having to assume the patient always presents as in the planning scan and so the "attenuation maps" obtained at each fraction may not have the same anatomy baseline as those pre-calculated. Furthermore, even the most carefully executed pre-treatment measurement protocols are assuming that the dose distributions will be produced in "the planning scan" patient. It is our belief that given the resources available on a purposely designed IGT machine that daily correction strategies or an ultimate adaptive therapy will be feasible in the near future and the time scales for its consideration are more dependent on the computer industry than the oncology manufacturers.

The last comment here should consider how these daily treatment plans will be generated. Current methodologies, that demand we contour structures as part of the IMRT prescription, may raise questions as to whether the contrast available in the MVCT images are sufficient. The achievable contrast was discussed earlier in this article. Work is underway, within various groups [37, 38] to automatically produce contours for MV portal (2D) images. This work should be adaptable towards the volumetric MVCT and enable us to produce such prescriptions without the need for manually contouring.

The final step, deformable dose registration, described in Figure 7 is concerned with the method that combines daily dose distributions to produce realistic treated distributions. Though it is potentially a subtle point in the first instance it really is quite an obvious strategy to want to use. Consider

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Figure 6. A sagittal reconstruction from the MVCT verification data set is shown in the top left box and the corresponding image from the planning data set underneath. The tinted blocks in the "checker-board" show the MVCT data. Once again the aberrations in the kV image due to prosthesis are not evident in the MV image. This figure was kindly provided by Dr Chester Ramsey III of the Thompson Cancer Survival Centre, Knoxville, Tennessee, USA.

Figure 7. The adaptive radiotherapy process map as defined by Mackie. The importance of an integrated volumetric imaging system in the treatment system is apparent from this diagram.
a prostate treatment and recall the potential problem introduced by differential rectal filling at each fraction. Let us consider the IMRT beams to be delivered to isocentre at the centre of the prostate, which remains essentially fixed in space, however the rectum/prostate interface is quite unstable throughout treatment moving in the anterior to posterior direction and therefore causing the anterior rectal wall to be appropriately spared on most occasions but treated with high doses on others. We are not really interested in what doses particular voxels or theoretical locations in the treatment plan receive. However, we are interested in knowing what dose the anterior rectal wall received. In the deformable registration [39–41] work developed by Ruchala [42] the daily MVCT data is deformed elastically in order to topographically match the planning CT images, once this elastic transformation has been computed it can be applied to the dose distribution associated with that fraction. Having performed this process to the data for all treatment fractions the “deformed” dose distributions can be added together and the true doses to each organ can be assessed. This approach is likely to be very powerful for contemporary treatment outcomes analysis.

Discussion

As stated elsewhere in this review, the provision of IGT does not require the helical tomotherapy delivery system, however as discussed it certainly provides several advantages in this process. Nevertheless, there are a number of reasons why it would be advantageous to use conventional equipment. For example (and not exclusively): familiarity — operationally and service considerations; availability — existing Linacs could be upgraded to include the required imaging platforms for IGT. If one of these new devices were installed in a centre then the issue of redundacy and guarding against unplanned treatment gaps (due to breakdown) in treatments is an important consideration. Under current popular IMRT acceptance/QA protocols it is not possible to create an alternative Linac-based IMRT solution at short notice. However, if we do believe that the strengths of this new technology lie in the fact that it can deliver (and verify) highly optimal treatment solutions then we should question whether un-optimal treatments should always be preferred in order to guard against such issues. There are certainly many clinics worldwide that have a single high energy Linac with electron treatment capability, so fear of lack of redundacy has not negated the use of Electron therapy!

In the section on optimization we presented an argument as to why the tomotherapy approach has merits over what is currently considered the more standard alternatives. In Figure 8 we present a clinical example for the treatment of a tumour in the base of tongue. These images were provided by Dr Cho of the Southeast Regional Cancer Centre in Tallahassee, Florida, USA. The colours of the curves in the DVH correspond to those of the contoured structures in the (inset) transaxial image. We note the excellent sparing of the each of the parotids and the cord, the majority of former getting less than 15 Gy and the latter less than 8–10 Gy.

In Figure 9 we present a very interesting example of a proposed total marrow irradiation protocol provided by Dr Schultheiss of the City of Hope Comprehensive Cancer Centre, California, USA. Again, the benefits afforded by the optimization and inherent ability to deliver such a modulated treatment are obvious. However, what makes such an approach remotely conceivable (and therefore the subject of such a study) is the ability to perform the on-line volumetric imaging. The treatment simulated in this planning study and the clinical treatment shown in Figure 5 demonstrate the ability of the helical tomotherapy device to treat “long” treatment volumes.

In this review we have discussed the adaptation of the conventional Linac design/configuration to provide IGT systems. There is also another purposely designed IGT machine available commercially. Though initially designed for radiosurgical applications the Cyberknife [43], manufactured by Accuray Inc. Sunnyvale, CA, USA, is ideally suitable to deliver highly conformal treatments and its use for extracranial treatments [44, 45] has been reported. This device comprises of a 6 MV waveguide mounted on a robot arm which has 6 degrees of rotational freedom enabling a large number of beam orientations and directions. The system also has a pair of kV X-ray tubes, with complimentary flat plate detectors, stereoscopically mounted. This type of imaging, although excellent for neurosurgical applications, does not provide the inherent advantage of volumetric MV or kV CT imaging that we have discussed for treatments outside of the brain. It was reported at the ESTRO in September 2003 meeting by Ma that some 5500 patients had been treated worldwide, 500 of which were extracranial treatments.

In summary, the ability to provide highly conformal treatments and on-line verification in an integrated unit is a highly desirable system for IGT; helical tomotherapy has this ability.

Conclusion

In this paper we have reviewed an exciting new technology which recently became commercially available. The helical tomotherapy system is a fully integrated purpose designed IMRT or IGT delivery system. It is beyond doubt that serial tomotherapy played a very important part in the history of IMRT to date, we look forward with interest to see whether helical tomotherapy becomes a significant part of the rest of our subjects history.
This article has been deliberately pitched to reach the majority of the intended (multidisciplinary) readership. I beg the indulgence of my mentors, whom will undoubtedly find some over-simplifications amusing, but hopefully not too irritating! We, the multidisciplinary UK community, often view trans-Atlantic developments with some awe, this article was intended to introduce and familiarize the reader with one such development and provide background understanding. It is a pleasure to acknowledge the financial support of Computerized Medical Systems, Hull and East Yorkshire Trust, the University of Hull (Clinical BioSciences Institute) and Yorkshire Cancer Research enabling the research within our group. We have no commercial sponsorship from Tomotherapy Inc. Finally, I would like to thank Dr Chris Nutting for his honouring me with the invitation to write about this subject and addressing the question posed in the title.

References


