Delivery of two-dimensional spatially-slowly-varying intensity-modulated beams by Jaws Only (JO) in rotate-translate mode.

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Abstract

IMRT can be delivered by Jaws-only (JO) provided some compromises are accepted. In this Letter it is shown how the use of a rotate-translate methodology (ROTJO), also employing only jaws, can lead to a delivery of a two-dimensional intensity-modulated beam wherein the modulation is spatially slowly varying.

1. Introduction

Despite the wide availability of methods to deliver intensity-modulated radiation therapy (IMRT) using a linear accelerator and a multileaf collimator or binary-slit collimator, there is still interest in pursuing the delivery of two-dimensional (2D) spatially-intensity-modulated beams (IMBs) using just the jaws of a linear accelerator (Webb 2006). Dai and Hu (1999) showed that, whilst so-called Jaw-only (JO) IMRT was less Monitor Unit (MU) efficient than MLC-based IMRT, it nevertheless was possible and might suit some Centres with JO equipment. En passant we may note that Webb (2002a,b) proposed to enhance the potential of JO IMRT by adding a tertiary mask. A commercial planning system (Prowess Panther) for JO IMRT has been independently developed and studies based on its use have again shown the potential for JO IMRT (Kim et al 2007, Mu and Xin 2009) as well as renewed interest in this methodology for actual clinical problems.

Planning for JO IMRT generally generically takes place by finding a set of JO-defined rectangular apertures that sum to give the required 2D IMB. Two basic classes of algorithm exist: (i) stripping components from a prescribed 2D IMB until there is zero residual (and within this class there are many sub-categories of component stripping (e.g. Webb 2002a)); (ii) direct aperture optimisation (e.g. Earl et al 2007). Inherent, however, in both these is the concept of creating a matrix of bixel fluences that, in principle, could vary greatly within the matrix and with large inter-bixel changes and gradients.

In this Letter we draw attention to a completely different way of using jaws to deliver IMRT and how to plan for this. The method would be most suitable for when the 2D IMB is spatially slowly varying with few high-frequency components.

2. Method

Delivery of IMRT is by translating a long, but narrow, JO-created slit of radiation in the direction normal to the long axis of the slit, varying the fluence delivered at each position along the path of translation. This is subsequently repeated for a number of collimator rotation angles in the range 0 - π, the 2D IMB being the sum of such “rotate-translate” contributions. For abbreviation we call this “rotate-translate Jaw-only IMRT” or ROTJO IMRT. The concept is shown in Figure 1. A necessity is that the area outside of the 2D IMB must be shielded by a secondary rectangular collimation, perhaps made of cheap and convenient Cerrobend. The slit is long enough to span the whole area of the 2D IMB and, without this additional collimation, would unwastefully irradiate outside this rectangle. Alternatively, with no mask collimation, the slit would be required to change its length with θ to fit the area of the IMB. This could be done either (i) by dynamically changing the orthogonal jaws as the JO-defined slit translates or (ii) by defining the square mask by the leaves of a MLC (varying with θ) just to perform a proof-of-concept experiment. (If a MLC were available then the rationale for the ROTJO method would vanish of course).

Consider a 2D IMB prescription, which we denote by $D_{\text{prescribed}}(x,y)$. A line integral through this prescription

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at some orientation angle $\theta$, and displacement $\gamma$ from the origin may be written

$$P(\gamma', \theta) = \int dx \, dy \, D^{x\gamma}(x, y) \delta(-x \sin \theta + y \cos \theta - \gamma')$$  \hspace{1cm} (1)

where $\delta$ is the Dirac delta function. These line integrals, $P(\gamma', \theta)$, constitute a Radon transform of the prescribed IMB. A central slice theorem and convolution-back projection formula follow in direct analogy to computed tomography (CT). Capitalising on the analogy between translate-translate-first generation CT, we may now see how to obtain the required intensities for the component slit contributions. In RTOJ, the measured ray-projections of x-ray CT are replaced by line integrals through a prescribed IMB. Further, in RTOJ, the mathematical process of the backprojection of a convolved x-ray projection in x-ray CT is replaced by the physical laying down of fluence by a slit of radiation. There is of course a fundamental difference (and potential difficulty), namely that (some) convolved projections of x-ray linear attenuation coefficient in x-ray CT can and have to be reordered in order to reconstruct the CT scan whereas fluence cannot be negative. How to cope with this is described below.

The planning technique is as follows (see also Figure 2):

1. The planning starts with a specification of the 2D IMB prescription $D^{x\gamma}_{\text{pres}}(x, y)$ on rectangular bixels with a side size $b$. The width of the scanning slit in the direction of scan is $w$. We suggest the requirement that $w \leq b$. Let there be $N_0$ collimator angles equally spaced in the angular range $0 - \pi$ at angular separation $\Delta \theta = \pi/N_0$. Let

$$\theta = k \pi, k = 0, 1, 2, \ldots, (N_0 - 1).$$

2. Form the projections $P(\gamma', \theta)$ of the bixel fluences in the rotated (by angle $\theta$) frame $(x', y')$ where the slit translation is in the $y'$ direction. When forming the projections, proper account was taken of the precise overlap of each slit with the bixels when it irradiates by subsampling the bixels with a regular grid of $L^2$ points within each bixel. In the illustrative examples we used $L = 10$ for computational efficiency. (The results were little different with $L = 100$). Hence each projection is given by

$$P(\gamma', \theta) = \frac{1}{w} \left( \frac{b}{L} \right)^2 \sum_{y'} D^{x\gamma}_{\text{pres}}(x, y)$$

where $N_0(\gamma', \theta)$ is the number of such subsampled locations in the projection. This is the discrete subsampled representation of equation (1).

3. The projections $P(\gamma', \theta)$ were convolved with a Ram-Lak filter (Ramachandran and Lakshminarayanan 1971) to create convolved projections $P^\ast(\gamma', \theta)$.

4. Since fluence cannot be negative, any such values for $P^\ast(\gamma', \theta)$ were set to zero.

5. The zero-adjusted convolved projections were backprojected into the matrix to create the delivered fluence map $D^{\text{del}}(x, y)$. Now this will not immediately be what is wanted, unless, as we showed, in passing, one (non-physically) were to ignore step (iv). Hence, instead (step (vi))

6. The zero-adjusted convolved projections were further iteratively adjusted by adding and subtracting "grains" of projected fluence until the delivered fluence $D^{\text{del}}(x, y)$ matched the prescribed fluence $D^{x\gamma}_{\text{pres}}(x, y)$ in a least squares sense. A "grain" is a very small element of fluence contribution. To achieve this a very large number $N_0$ of iterations was performed (in the illustrative examples $N_0 = 5 \times 10^5$). Each grain was accepted if it led to a closer agreement than without the grain and vice-versa. Positivity of adjusted projections was maintained throughout of course. After many iterations, with a fixed starting grain size, the grain was gradually reduced to zero over the final iterations. The "distance to agreement" was characterised via the maximum, minimum and r.m.s. standard deviation of the difference $[D^{\text{del}}(x, y) - D^{x\gamma}_{\text{pres}}(x, y)]$.

7. When such long iterations are performed there is a danger of a disconnect arising between the iteratively developed convolved projections and the delivered fluence distribution even though double-precision arithmetic was performed. Hence, a posteriori, a single-step recomputation was made of $D^{\text{del},\text{comp}}(x, y)$ directly from the iteratively adjusted $P^\ast(\gamma', \theta)$. A checksum (the summed absolute difference between these two computations) was computed to show that $D^{\text{del},\text{comp}}(x, y)$ was identical (with a very high tolerance) to $D^{\text{del}}(x, y)$.

8. Finally the efficiency of delivery was computed, being the ratio of the largest value of $D^{x\gamma}_{\text{pres}}(x, y)$ to the sum of the adjusted convolved projections $\sum_\gamma \sum_\theta P^\ast(\gamma', \theta)$.

3. Results
Figure 3 shows one example from the computer modelling. Figure 3a shows the prescription and Figure 3b shows the delivered fluence. For this example there were just \( N_p = 6 \) projections (6 translations of the JO-defined slit). The maximum, minimum and r.m.s. errors were 0.0433, -0.0397 and 0.0108. The efficiency was 0.8379 (459.464 MLs needed). The checksum was zero to better than 2 decimal places. Figure 4a shows a second example but one in which the bixels were now much more discrete and took integer values. Figure 4a shows the prescription and Figure 4b shows the delivered fluence. For this example there were again just \( N_p = 6 \) projections (6 translations of the JO-defined slit). The maximum, minimum and r.m.s. errors were 0.8576, -0.6426 and 0.1938, clearly larger than in the case described above. The efficiency was 0.0359 (445.357 MLs needed). The checksum was zero to better than 2 decimal places. Even so, the moderate differences between the prescription and the delivery may not be too important once a number of such beams from different gantry angles are combined in IMRT delivery, provided the number of such independent beams is large.

4. Discussion

A method has been developed that can generate a spatially-slowly-varying modulation of intensity within a 2D IMRT. The method comprises translating a jaw-defined slit of radiation across the collimated field and summing the contributions from a number of collimator orientations (ROTJO). The fluence in the slit would be either modulated by varying the output of the linac and using constant speed of translation or by employing a variable dwell time with constant fluence output. It has been shown that this method is, as expected, less successful for highly bixelated fluence distributions (where the conventional JO decomposition method works best). Planning for this method of delivery has strong analogies with the theory of x-ray CT but, given the impossibility of negative modulation, requires a second step of iterative adjustment after the CT-like first stage. It has been shown, in computer modelling, that just 6 rotations can give a very satisfactory outcome. Artificial use of the computer model with say 90 rotations gave an even closer fit but would be impractical.

Experience has shown that very long iterations (beyond the order of \( 10^6 \) and up to \( 10^7 \)) can lead to even closer agreement of the delivered and prescribed 2D IMB. The only price paid is increased computer times. The first stage takes almost no time at all and \( 10^7 \) iterations take about 30 minutes on a Dell Optiplex 755 computer. The delivery MU-efficiency is quite low but that is expected and not inconsistent with the previous IMRT studies in principle it could be built into a more sophisticated version of the second stage iterative process.

It should be mentioned that jaw transmission is not a problem in general. Clearly, whenever a slit is being irradiated, the remainder of the masked field, which is shielded by the jaws, receives a leakage radiation \( \tau \) times the fluence delivered to the slit. However, this is not a problem since it can be completely built into the iterative process such that the delivered fluence becomes the sum of all open irradiations and all transmitted irradiation. The illustrative computer-modelling code was extended by this enhancement and with \( \tau = 0.01 \) and \( \tau = 0.03 \) the delivered 2D fluence distribution was almost identical to that shown in Figure 3b. Of course, a by product is that the efficiency actually increases as \( \tau \) increases because less monitor units need to be delivered when transmitted radiation contributes. A caveat is that clearly the prescription cannot have lower fluences than the sum of the transmitted fluences, the situation being entirely analogous to the way leakage is included in the dynamic MLC ("sweeping window") technique (Spirou and Chiu 1994). To properly account for penumbra as well as transmission for small-area fields is a challenging problem but methods exist to tackle this. We may cite two different pieces of equipment that in the past have required such an analysis. One was the NOMOS MIMIC (Weeb and Oldham 1996) and the other was the Variable-Aperture Collimator (Webb et al. 2003 and Anderson 2009). In each case the delivered fluence was the superposition of primary with penumbra and transmitted fluence.

In conclusion all that is required of the accelerator is the use of translating jaws and the ability to rotate the jaws ("head twist"). This Letter draws attention to the feasibility of creating some spatially-slowly-varying 2D IMBs via ROTJO. It is not suggested that this can challenge conventional IMRT delivery but it may be of interest to some Centres.

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Figure captions

Figure 1: Illustration of the delivery method. An open slit of width \( w \) translates at an angle \( \theta \) across the
aperture delivering a variable fluence $P^*(y', \theta)$.

Figure 2: A block resume of the chain of planning events.

Figure 3: (a) a spatially-slowly-varying 2D IMB prescription $D_{\text{pres}}(x, y)$ and (b) the corresponding 2D IMB delivery $D_{\text{del}}(x, y)$. Units are MU. Axes are in cm. $b$ and $w$ were set to 0.5 cm. The 2D IMB is on a $32 \times 32$ grid.

Figure 4: (a) a more bixelated (discrete) 2D IMB prescription $D_{\text{pres}}(x, y)$ and (b) the corresponding 2D IMB delivery $D_{\text{del}}(x, y)$. Units are MU. Axes are in cm. Axes are in cm. $b$ and $w$ were set to 0.5 cm. The 2D IMB is on a $32 \times 32$ grid.

References


Spirou S V and Chui C S 1994 Generation of arbitrary intensity profiles by dynamic jaws or multileaf collimators Med. Phys. 21, 1031-41


Webb S and Oldham M 1996 A method to study the characteristics of 3D dose distributions created by superposition of many intensity-modulated beams delivered by a slit aperture with multiple vanes Phys. Med. Biol. 41, 2135-2153
Fluence is delivered only in the bixels within the box (outside is masked)

Direction of JO translating

Open slit aperture defined by jaws

Figure 1
Given a 2D IMB fluence prescription on a grid of bixel size b

Select number \( N_b \) of translating IO beams at spacing \( \delta_0 \); select subsampling level \( L_b \), select jaw width \( w (\leq b) \) for delivery

Project the 2D IMB into projection space ensuring this fully spans the 2D prescription matrix

Convolve the projections with Ram-Lak filter

Set negative convolved terms to zero

Project the adjusted convolved projection data into delivered fluence space

Iteratively adjust the convolved projections, maintaining positivity, and accept changes that bring the delivered fluence closer to the prescription

Have \( N_b \) iterations been completed?

Stop after required number \( N_b \) of iterations

Output is the delivered fluence pattern; the IO scanning MU profiles; measures of “closeness of fit to prescription” and efficiency

Figure 2