Improving radiotherapy treatment for left-sided breast cancer
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Citation for published version (APA):
Cho, B-C. J. (2004). Improving radiotherapy treatment for left-sided breast cancer
Chapter 5

**THE DEVELOPMENT OF TARGET-EYE-VIEW MAPS FOR SELECTION OF COPLANAR OR NON-COPLANAR BEAMS IN CONFORMAL RADIOThERAPY TREATMENT PLANNING**

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5.1 Abstract

Three-dimensional conformal radiotherapy allows the use of tightly conformed, multiple coplanar or non-coplanar beams. However, visualizing the spatial relationships between the target volume and adjacent critical structures is not always obvious or intuitive. Tools such as beam’s eye view (BEV) have aided in this process and have been very useful. In this study, a target-eye-view (TEV) map is developed as a functional extension of BEVs. The TEV map for a critical structure is created by checking the BEVs for all gantries and table rotations. For each possible BEV, the amount of overlap between the planning target volume (PTV) and the organ at risk (OR) is determined. This information is presented in a Mercator spherical map, where the color tone indicates the amount of overlap between the PTV and the OR. A composite TEV map is then created by summing the TEV grading scores for all ORs. The composite map shows beam orientations with the most overlap being light and the least overlap being dark, thus simplifying the selection of appropriate beam angles. The accuracy of the TEV maps has been confirmed separately with corresponding BEVs generated by a three-dimensional treatment planning system.

5.2 Introduction

The past decade has witnessed significant advancement in the science of radiotherapy. Three-dimensional conformal radiotherapy (3DCRT) has used tightly conformed, multiple coplanar or non-coplanar beams to allow dose escalation without increasing normal tissue complications. The use of non-coplanar beams, however, adds significantly to the number of possible beam directions and combinations as compared to coplanar beam arrangements [1]. If $5^\circ$ increments are assumed, then an estimated $3 \times 10^{20}$ possible beam combinations exist for a six-field plan [2].

In the few-numbered beam (oligobeam) intensity modulation approach, appropriate beam selection is critical. Söderström et al have shown increased variability of the complication-free tumor control probabilities ($P^*$) as a function of the beam direction in oligobeam treatments, suggesting the importance of optimal beam orientation for oligobeams [3]. Conversely, when many beams are used ($\geq 5$), beam orientation becomes less important in the overall optimization. It is suggested that the optimal use of 2-5 beams can yield tumor control probabilities and normal tissue complication probabilities comparable to those of an optimized infinite beam arrangement [1,4].

With current visualization tools in treatment planning, the overall spatial relationships between a target volume and adjacent organs at risk (OR) may not be obvious, or intuitive. The anatomical relationships can be difficult to appreciate in complicated disease sites such as the pituitary and the base of the skull, where the planning target volume (PTV) is surrounded by several ORs in close proximity. Beam’s eye view (BEV) is a commonly used tool to facilitate the visualization of these structures. Since its introduction and implementation, BEV has aided treatment planning, particularly in the use of oblique beams [1,5-8]. A BEV identifies volumes of overlap between the target volume and adjacent critical structures from the beam’s perspective. Based on this information,
the dosimetrist may apply further different beam-modifying devices to achieve an optimal dose contribution for the treatment beam. Nevertheless, the important task of selecting optimal beam orientations still requires a separate review of many BEVs. BEV volumetrics, introduced as an aid to treatment plan development and evaluation, can plot the fraction of the volume of interest intersecting the beam as a function of gantry angle [9,10]. A series of plots with different table angles can then be compared to determine the most optimal beam orientation. This idea was further refined by McShan et al., who developed innovative volumetric globe and phi-theta map displays [11].

The target-eye-view (TEV) map is a modified left-handed Mercator spherical map projection which visually represents all possible BEVs passing through the isocenter within a specified target. The concept of the TEV map, although related to volumetrics, is more of a functional extension of BEVs. The TEV map serves the same function as BEVs but does not limit itself to a single view. It, in effect, determines the overlap for every possible BEV and displays the results as a map. Each point of the map represents a unique BEV and its color tone indicates the type of overlap between the PTV and the OR. Beam orientations with significant PTV and OR overlap are shown in light tones, while orientations with insignificant overlap are displayed in dark tones. The major difference between TEV and BEV volumetrics, as used by McShan, is the use of scoring systems. In a sense, volumetrics is a type of scoring system using only overlapping partial volumes. TEV introduces other relevant variables (such as margins, types of overlaps, and relative importance of critical structures) into the map so that additional useful information can be applied. By summing the TEV maps for several ORs, a composite TEV map incorporating comprehensive and relevant clinical parameters is created.

5.3 BACKGROUND

The standard coordinate system for radiologic imaging uses a right-handed Cartesian coordinate system \((x, y, z)\). However, spherical coordinates \((r, \theta, \phi)\) are more convenient for mapping as they are better correlated with the treatment gantry angles \((\gamma)\) and table angles \((\varnothing)\), and they are easily obtained from the Cartesian coordinates \((x, y, z)\) provided by the CT scan (Fig. 1). These special spherical coordinates differ from the standard spherical coordinate system in several important aspects. First, movement of the table is limited to the \(xz\) plane. Second, the gantry rotation is fixed on the \(xy\) plane. Third, when the gantry is rotated to 0°, the central axis follows the \(y\) axis. Last, the treatment spherical coordinates, unlike the standard system, are left handed (the angle from the positive \(x\) to the positive \(y\) axis moves counterclockwise when observed along the positive \(z\) axis).
The developed TEV map uses a left-handed Mercator spherical projection where $\theta=0^\circ$ lies on the $yz$ plane so that consistency with the treatment coordinates is maintained. The latitude (elevation) lies along the ordinate and the longitude (azimuth) lies along the abscissa. Thus, the north pole ($\varphi=90^\circ$) describes an inferiorly oriented beam. For an isocentric beam arrangement, all possible beam directions can then be characterized by the spherical parameters $\theta$ and $\varphi$ for a line drawn from the source to the isocenter (i.e., central axis).

### 5.4 MATERIALS AND METHODS

All computer calculations were performed on a Pentium 133 Mhz personal computer. The TEV mapping software was developed on MATLAB v5.1.0.421 (The Math Works, Inc, Natick, MA). This software was chosen mainly for its economy, ease of use, and flexible graphing capabilities. The Helax Treatment Managing System (TMS), v4.1 (Helax, AB, Upsalla, Sweden) was run on a Digital Alphastation 400 under the OpenWindows operating system environment.

A Picker PQ 2000 CT scanner (Picker International, Inc., Cleveland, OH) was used to obtain CT datasets of the sites of interest. The scanned data were imported into the treatment planning computer. Gross tumor volumes, PTVs, and ORs were contoured in TMS [12] and exported via the radiation therapy oncology group (RTOG) export format. All of the beams were isocentric and the origin was defined at the isocenter within the gross target volume.
The test case of a pituitary tumor patient with 8 ORs was imported into MATLAB to prove the concept. Adjustable parameters such as source-to-axis distance (100 cm, isotropic penumbra margin size around the PTV) 5 mm, and mapping resolution (1°) were defined. The program performed an overlap check of the BEV for all $\theta$ and $\phi$ combinations. The steps followed are outlined in the flow chart of Figure 5-2.

A. **Determine $\theta$ (azimuth) and $\phi$ (elevation) that correspond to the central axis passing through the point source and isocenter**

First, all permissible or forbidden beam orientations are determined. Angles may be forbidden if the gantry and table collide.

B. **Determine the PTV and OR outlines cast from the point source**

For each volume of interest, the Cartesian coordinates are transformed and translated to spherical coordinates centered at the point source (i.e., inside the gantry head) to simplify the calculation of beam divergence. Rays from the point source cast the shadow of the PTV and OR on a virtual plane perpendicular to the central axis at isocenter.

C. **Determine type of overlap between the outline of the PTV and OR**

The distance between the PTV outline and the nearest point of the OR in the plane perpendicular to central axis is calculated. If the distance is negative or zero, then at least one point of overlap exists between the OR and PTV. This is called a **hit**. If the entire critical structure lies behind the isocenter, then a **distal hit** is identified. The situation is analogous to that of an exit beam. If any part of the OR lies at or in front of the isocenter, then a **proximal hit** is identified. If the distance between the PTV and OR is greater than the geometric penumbra, then no overlap is assumed and this is called a **miss**. If the distance is within the penumbra, then it is called a **marginal hit**. This implies that there is some overlap between the treatment target volume and OR [Figure 5-3(a) and (b)].

D. **Repeat until completion**

Steps B and C are repeated for each OR. The beam orientation is changed by the mapping increment and the entire sequence is repeated until every $\theta$ and $\phi$ combination is checked.

E. **Determine collision array**

A collision array is constructed when BEVs are checked. A collision array is a matrix containing the overlap information for each OR at each BEV. If the mapping resolution is $1^\circ$, then the collision array has $361 \times 181 \times n$ elements, where $n$ is the number of ORs.

F. **Calculate TEV scores**

From the collision array, a TEV grading score for each individual critical structure can be generated. To obtain a composite grading, each critical structure is
arbitrarily assigned a relative criticality score. For example, at a prescribed dose of 50 Gy, the retina (orbit) is judged to be more critical to spare clinically than the brainstem, so a score of 2 versus 1 is assigned. The type of overlap is also assigned a relative collision score (Table 5-1). The overall composite score combines the scores of every critical structure for a given orientation. Therefore, high composite scores may suggest more critical structures and/or more critical overlap.

G. Display TEV map

The TEV scores can be plotted onto a flat projection where each point represents a unique BEV. BEVs with high scores are light, and low scores are dark. Two methods are used to display the information: the spherical TEV map and the treatment TEV map. Spherical TEV map coordinates (elevation and azimuth) can be converted to treatment TEV map coordinates (table and gantry). The former is visually more intuitive, while the latter facilitates easier use in treatment planning.

Table 5-1. Relative collision and criticality scores for different overlap and critical structures. Higher scores represent more significant structural overlap and/or more important critical structures. Arbitrary clinical judgement is applied in this study for the proof of concept.

<table>
<thead>
<tr>
<th>Type of overlap</th>
<th>Collision score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximal hit</td>
<td>1.0</td>
</tr>
<tr>
<td>Marginal hit</td>
<td>0.8</td>
</tr>
<tr>
<td>Distal hit</td>
<td>0.7</td>
</tr>
<tr>
<td>Miss</td>
<td>0.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Critical structure</th>
<th>Criticality score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chiasm</td>
<td>4</td>
</tr>
<tr>
<td>Optic Nerve</td>
<td>4</td>
</tr>
<tr>
<td>Optic globe</td>
<td>2</td>
</tr>
<tr>
<td>Cavernous sinus</td>
<td>1</td>
</tr>
<tr>
<td>Brainstem</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 5-2. A simplified flow chart of the target-eye-view (TEV) mapping program. Planning target volume, organ at risk, and beam's eye view are abbreviated as PTV, OR, and BEV, respectively.
Figure 5-3. (a) Lateral view of a radiation beam along the central axis. The ‘+’ (symbol) in the circle is the isocenter within the planning target volume (PTV). Various organs at risk (A, B, C, and D) exist around the PTV. The outer-most lines delineate the geometric penumbra. Both A and B have at least one point of overlap. A is a distal hit and B is a proximal hit. C is a miss. D is a marginal hit. (b) Beam’s eye view (BEV) along the central axis. The point source projects shadows from the planning target volume (PTV) and organs at risk. The outermost circle delineates the geometric penumbra. Both A and B are hits. C is a miss. D is a marginal hit. This BEV corresponds to a point on the spherical target-eye-view map.

5.5 Results

Figure 5-4. A spherical target-eye-view map for the left optic globe. The lighter central area represents proximal hits, the circumscribing gray area represents marginal hits, and the darker area on the left represents distal hits. Note that the proximal and distal hits lie antipodal to each other. The upper portion of the distal hits overlaps with forbidden angles.

This study reveals several characteristics of a spherical TEV map. In the TEV map for the left optic globe (OR), the distal hits that lie antipodal to the proximal hits circumscribe an area larger in comparison to the latter due to beam divergence (Figure 5-4). Structures lying closer to the PTV or the poles tend to block the beam more and hence
appear larger on the TEV map. An optic chiasm located immediately adjacent to the PTV may offer no complete misses in its TEV map. This implies that one cannot totally spare the chiasm when the PTV is too close, regardless of beam direction (Figure 5-5).

A composite TEV map displays problematic orientations as light areas (Figure 5-6). For example, the lightest areas in the pituitary TEV map are clustered around the beam portals which pass through the eye and optic nerves. As spherical TEV map coordinates cannot be directly applied as treatment gantry and table angles, a treatment TEV map is derived from the spherical TEV coordinates so that one can read directly from the axes (Figure 5-7).

![Figure 5-5](image-url)

**Figure 5-5.** A target-eye-view (TEV) mapped sphere and the corresponding three-dimensional structural anatomy for an optic chiasm. Structures A and B, the planning target volume (PTV), and optic chiasm, respectively, are depicted inside a transparent TEV mapped sphere. The patient is inverted and facing the right, and the other structures (C-optic nerves, D-left optic globe, E-right optic globe) are provided for orientation. Isocenter is within the PTV and lies concentric with the mapped sphere. The dark area above represents forbidden angles, where the gantry and table collide. The grey area in the middle represents distal hits, where the entire critical structure lies beyond the isocenter. The light area below represents proximal hits, where part of the critical structure lies closer than the isocenter. No complete misses are seen since the chiasm is hit, at least partially, regardless of the beam direction.
Figure 5-6. A composite spherical target-eye-view map for a patient with pituitary tumor. Lighter areas represent beam's eye views with more structural and/or more critical type of overlap. The arrow is arbitrarily chosen to point out corresponding BEVs between different mapping displays of Figure 5-6 and Figure 5-7.

Figure 5-7. A treatment target-eye-view map. The arrow marks the same BEV \((\theta=48^\circ, \varphi=23^\circ)\) in both maps of Figs. 5-6 and 5-7. According to the lightness of the spot, placing a beam here will not provide an optimal BEV.

To test the validity of the TEV mapping software, beam orientations were randomly selected by the computer. Helax TMS generated the BEVs of these particular beam angles so that the collision array created by the mapping code could be verified. The type of overlap for each OR, as predicted by the collision array, was identified and confirmed separately with the BEV. There was a 100% correspondence for all of the structures studied. Thirty-eight percent of the possible BEVs are forbidden due to gantry
and table collisions. Not surprisingly, this area lies on the northern hemisphere of the spherical TEV map and corresponds to an inferiorly oriented beam.

5.6 Discussion

Although various beam optimization algorithms such as simulated annealing and inverse planning exist, conventional treatment planning places practical limits on the number of beams that can be evaluated. For the most part, beam selection is an *ad hoc* iterative process. A TEV map represents a simple, valid, and convenient tool for treatment planning. It simplifies beam selection by suggesting certain (dark) beam orientations and warning against others (light). By partitioning overlap outcomes into hits and misses, TEV maps use a relatively simple geometric determination algorithm, and are therefore quicker to calculate than those using volumetrics. Its utility is readily seen when favored beam orientations are gleaned at a glance. Each point on a TEV map represents a BEV with a predetermined margin around the PTV. For example, in our case of pituitary tumor, we can place an anterior beam and be confident that it will miss both optic globes if the TEV map shows no overlap with these critical structures.

The TEV map’s main utility lies in the selection of beam orientations. Other beam parameters, such as weighting and wedging, are not addressed. In the oligobeam approach, the latter parameters may be less difficult to optimize since the solution can be well provided through beam intensity modulation [4]. Therefore, we envision automated beam optimization as a two-step process, where optimal beam orientations and arrangements are first selected with the aid of a TEV map. These beams are further optimized for weight, modifying devices, and energies by other more suitable optimization algorithms. Placing of multiple beams in an optimized fashion will be discussed in a follow-up paper. A geometric optimization method will maximize both the angular displacement and favored BEVs. For example, the ideal geometric arrangement for four beams would follow the vertices of a tetrahedron to its geometric center. The most favored BEVs are then selected from the TEV in best accordance with the identified angular displacement between the beams.

The lack of empirical dose-volume data, as it relates to tumor control and normal tissue complications, presents difficulties in formulating biologically meaningful scoring rules. The rules used in this study to rank the relative importance of critical structures and type of collisions are, for the most part, arbitrary and rely heavily on clinical judgment. These parameters are adjustable, and must ultimately be tailored to the individual patient to reflect tissue complications and tolerances. Complication-free tumor control probabilities \( (P^-) \) [3] attempt to compare probable treatment effects objectively between identical structures. However, the relative importance between different structures again becomes a matter of clinical judgment. The scoring will be improved as new data become available from ongoing multicenter dose escalation trials.
For very interiody directed beans and/or wide patients, an adequate number of CT slices is required in order to give a proper representation of the entire relevant anatomy. The TEV map can mistakenly allow beams to pass through an obstructing shoulder if the patient is not scanned low enough to include it.

At present, the TEV mapping program is not fully optimized to minimize the calculation time. Approximately 3-4 h are required to complete a TEV map of an average pituitary tumor patient with eight critical structures at a 1° mapping resolution. The software in this study has been used to test the feasibility of the TEV map with the speed of execution as a secondary goal. Once the program is compiled, we expect to improve the running time to 20-30 min. Further gains are expected with code optimization, faster computer processors, sites with fewer critical structures, and coarser mapping resolutions (i.e., 5° increments).

5.7 ACKNOWLEDGMENTS

The authors wish to thank G. Dundas, L. Underwood, and C. Field for their invaluable assistance. This study was supported by the Alberta Cancer Board and Alberta Cancer Foundation.

5.8 REFERENCES


