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PHYSICS CONTRIBUTION

A CUSTOM THREE-DIMENSIONAL ELECTRON BOLUS TECHNIQUE FOR OPTIMIZATION OF POSTMASTECTOMY IRRADIATION

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Purpose: Postmastectomy irradiation (PMI) is a technically complex treatment requiring consideration of the primary tumor location, possible risk of internal mammary node involvement, varying chest wall thicknesses secondary to surgical defects or body habitus, and risk of damaging normal underlying structures. In this report, we describe the application of a customized three-dimensional (3D) electron bolus technique for delivering PMI.
Methods and Materials: A customized electron bolus was designed using a 3D planning system. Computed tomography (CT) images of each patient were obtained in treatment position and the volume to be treated was identified. The distal surface of the wax bolus matched the skin surface, and the proximal surface was designed to conform to the 90% isodose surface to the distal surface of the planning target volume (PTV). Dose was calculated with a pencil-beam algorithm correcting for patient heterogeneity. The bolus was then fabricated from modeling wax using a computer-controlled milling device. To aid in quality assurance, CT images with the bolus in place were generated and the dose distribution was computed using these images.
Results: This technique optimized the dose distribution while minimizing irradiation of normal tissues. The use of a single anterior field eliminated field junction sites. Two patients who benefited from this option are described: one with altered chest wall geometry (congenital pectus excavatum), and one with recurrent disease in the medial chest wall and internal mammary chain (IMC) area.
Conclusion: The use of custom 3D electron bolus for PMI is an effective method for optimizing dose delivery. The radiation dose distribution is highly conformal, dose heterogeneity is reduced compared to standard techniques in certain suboptimal settings, and excellent immediate outcome is obtained.

Postmastectomy irradiation, Conformal electron therapy, Electron bolus.

INTRODUCTION

The delivery of postmastectomy irradiation (PMI) can present many challenges to the radiation oncology team. The radiation dose distribution must include the original location of the primary tumor and the regional lymph nodes while simultaneously minimizing the dose to normal tissues (heart, underlying lung, contralateral breast) which are not at risk for recurrent disease. Varying chest wall thickness, contour, and slope also add to the technical difficulty of PMI, as well as the density of the component tissues (skin, subcutaneous tissues, bone, muscle, and lung). These physical factors may be altered and further complicated by the mastectomy technique used, which could result in chest wall defects. The original site of tumor involvement also may present a challenge as it may be located where typical field junctions are placed and where "hot" or "cold" spots may be present. These potential deficiencies may compromise the goal of PMI, which is to eliminate residual viable tumor in tissue remaining after standard mastectomy while minimizing complication risk (1).

Many oncologists thought that systemic therapy would eliminate all residual viable tumor and thereby change the indications for PMI; however, this has not been the case. Recent trials indicate that as systemic therapy becomes more effective, achieving locoregional control with PMI is even more important and is contributing to improved survival (2–4). Data from patients treated with outmoded techniques and equipment have shown increased deaths from cardiac complications after PMI; however, more recent studies reveal that carefully planned PMI avoids these types of complications (5, 6). The chest wall electron technique with a bolus material is one method that can be used.

Archambeau *et al.* described a bolus technique to be used with chest wall electrons that controlled the penetration of

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the electron beam over a large area (7). Their technique used individual wax strips and constructed a wax profile by adding strips over a wax base plate to achieve an acceptable result. Beach *et al.* also described a bolus technique, but used ultrasound technology and limited computed tomography (CT) images to construct their bolus (8). Both the technique used by Archambeau *et al.* and Beach *et al.* lacked sophistication of dose calculation, bolus design, and bolus fabrication. Effects of electron scatter were ignored. The sloping surfaces of the technique by Beach *et al.* could not be taken into account. The sharp edges of the wax strips of the technique of Archambeau *et al.* generated hot and cold spots within the patient.

In this present work, we utilize a conformal electron technique for optimizing PMI. Our technique uses superior technology for bolus design and fabrication. CT-based images are used by the 3D treatment planning system for bolus design and verification. The bolus is also designed using a 3D dose algorithm capable of accounting accurately for scatter. A computer-controlled mill constructs the custom bolus with smooth surfaces. This conformal technique, therefore, represents a substantial technological advancement in electron therapy and gives the radiation oncologist an additional tool for delivering careful and optimal PMI.

The current policy at The University of Texas M. D. Anderson Cancer Center is that regional lymphatic and chest wall irradiation is indicated after mastectomy: 1) for all Stage III patients; 2) for all Stage II patients with four or more axillary nodes involved with metastatic tumor or those with any positive nodes with gross (>2 mm) extranodal disease in the axilla; 3) for all patients with positive margins; and 4) for all patients with locoregional recurrence. Chest wall irradiation is usually given via tangential photon technique with a separate matched electron internal mammary chain (IMC) field. The IMC field treats the nodal areas, as well as the medial chest wall. The use of the IMC field compared to tangent fields without the IMC can also decrease the lung volume treated in the tangential fields. This standard technique is optimal for patients with a thick or irregular sloping chest wall. Patients who have a thin homogeneous chest wall may be treated with a chest wall electron technique using separate electron fields as described elsewhere (9, 10). Some patients are not optimally treated with either technique. Examples include patients with a chest wall defect where standard fields would incorporate a substantial amount of lung (>3 cm or >30% of volume) in the treatment fields, and patients at high risk for recurrent disease sites in areas of typical field junctions. In these situations, treatment modifications must be considered. This paper describes such a modification—a custom 3D electron bolus technique for electron beam therapy to the chest wall and IMC. This technique optimizes the dose distribution throughout the chest wall and IMC while sparing normal tissues. Two patients who benefited from this option are described: one with altered chest wall geometry (congenital pectus excavatum), and one with recurrent disease in the medial chest wall and IMC area.

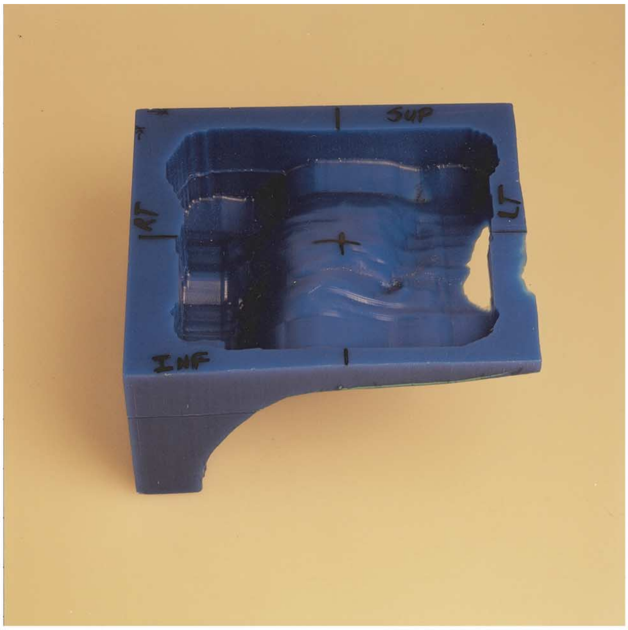
METHODS AND MATERIALS

Treatment planning

The patient was placed in treatment position with the ipsilateral arm elevated and supported by a Vac-Fix system (Soule Medical Corp., Tampa, FL). Markings were then made on the patient at midline and at the upper and lower borders of the treatment field. These landmarks were wired with radiopaque material. Multiple CT slices were taken with a separation of 5 mm. Treatment planning was done using our in-house 3D treatment planning system (11). After CT images of the patient were loaded into the treatment planning system and the patient skin surface was outlined, the physician outlined the planning target volume (PTV), i.e., the volume of the patient that should receive 90% of the given dose. After the beam orientation was chosen, the source-to-surface distance of the beam was set to 105 cm to allow for the electron bolus to be placed between the patient and the electron applicator. The shape of the electron beam field was drawn in the beam's-eye-view, and its edge was 1–1.5 cm outside of the PTV to allow for the penumbra of the electron beam. The electron bolus design used algorithms developed by Low *et al.* (12) at this institution. The following bolus operators were used: a creation operator defined the thickness of the bolus based on radiologic depth of the target volume; modification operators refined the bolus shape accounting for electron scattering; and an extension operator extended the bolus outside of the field to account for beam penumbra.

The dose was computed using a 3D pencil-beam algorithm with heterogeneity corrections (13, 14), and the bolus shape was computed as part of the dose calculation process (11). Ray tracing from the electron source to the patient surface computed the distal (inner) surface of the electron bolus, which lies in contact with the chest wall. The proximal surface was computed using the operators described above. After the dose was computed, the physician reviewed the treatment plan on the planning workstation. If necessary, the electron bolus operators were modified, and the dose was recomputed. Figure 1 shows the final bolus shape for one of the cases presented here.

The accuracy of the pencil-beam algorithm, reviewed by Hogstrom and Steadham (15), should be the same with bolus as without bolus, as the bolus can be considered part of the patient. However, the accuracy becomes more significant as the dose distribution is conformed to the PTV. For chest wall irradiation, the dose to the PTV can be expected to be accurate within 5%, as the bolus and chest wall are sufficiently water equivalent, and the bolus is designed to have a smooth surface with gradients typically less than 30°. Depth dose in chest wall and lung has been shown to be accurate within 4% in regions of side-scatter equilibrium. Dose errors as great as 8% can be expected near the lung–mediastinum interface; however, such errors would have minimal impact on the lung dose–volume histogram and hence little impact on the treatment plan. Newer dose algo-



(a)

(b)

Fig. 1. Superior (beam's eye) view and inferior view of a custom 3D electron bolus used for right-sided PMI. The isocenter and laser markings for patient setup verification are shown. Inferior, right (lateral), left (medial), and superior (cranial) borders are labeled.

rithms that can calculate dose within 4% accuracy for these conditions (15) were not available for this study.

Bolus fabrication

After an acceptable treatment plan was obtained, a text description of the electron bolus was transferred to a personal computer that controlled the bolus milling, which was done using an inexpensive tabletop milling machine. The milling process and algorithms have been described by Antolak *et al.* (16). The electron bolus was fabricated from modeling wax, a polystyrene-like material with radiation properties previously described by Low and Hogstrom (17). The total fabrication time was approximately 10 h. The fabrication process has recently been moved to a full-size milling machine to reduce the fabrication time to approximately 3 h, which is more clinically acceptable.

Quality assurance

After the electron bolus was fabricated, CT images were repeated with the electron bolus on the patient surface. Fiducial marks, engraved on the electron bolus as part of the fabrication process, were used to align the electron bolus with the patient skin surface. The CT images were visually inspected to verify that the bolus fit against the chest wall without air gaps that could affect the dose distribution. The repeated CT images were also used to generate a "final" treatment plan, which was physician-approved and placed in the patient treatment record. The patient was then treated with the electron bolus using a single anterior chest wall/IMC field. Figure 2 shows the electron bolus placed on the chest wall for treatment. A supraclavicular/axillary apex field was also employed. The junction between the two fields was moved 0.5 cm twice during the treatment course to avoid excess dose due to potential overlap of the fields.

RESULTS

The first case demonstrates the usefulness of the 3D custom bolus in compensating for suboptimal anatomy. The patient was 55 years old and postmenopausal. She presented to her local physician with a T4N1 M0 poorly differentiated adenocarcinoma of the medial right breast. She received three cycles of preoperative chemotherapy (doxorubicin and taxotere) followed by modified radical mastectomy and then an additional three cycles of the same chemotherapy. She was noted to have a prominent pectus excavatum deformity on physical examination (Fig. 3), which represented a treatment dilemma, because conventional tangential photon fields with an IMC would have included substantial lung tissue. "Wide" tangential photon fields would have required inclusion of the contralateral breast tissue in the radiation volume; standard chest wall electrons also would have yielded similar suboptimal results because of the location of her exaggerated chest wall curvature (Fig. 4). The 3D custom bolus technique was therefore used.

Because she presented with possible inflammatory breast cancer, she was initially treated to 51 Gy given dose at 1.5 Gy per fraction twice daily with 6-h interfraction interval with a single 16-MeV electron field. The treatment was planned to cover the PTV as outlined by the physician with the 90% (of given dose) isodose line. The resultant isodose distribution in a transverse plane is shown in Figure 4. As demonstrated, there was minimal dose to normal tissues (particularly the underlying lung) and acceptable coverage

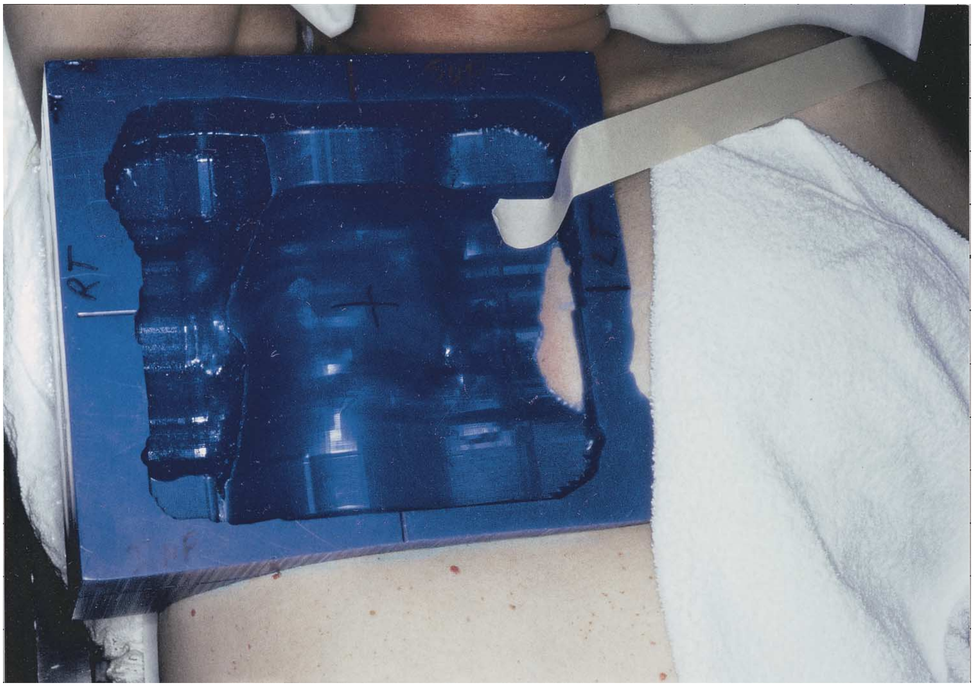


Fig. 2. The custom 3D electron bolus in treatment position. The patient is immobilized using the VAC-Fix system. The isocenter and laser markings for patient setup verification are shown. Superior (cranial), right (lateral), left (medial), and inferior (caudal) borders are labeled to assist in setup and verification.

of the chest wall. Further adjusting of the bolus thickness during the design process was considered; however, more closely tracking the planning volume than shown would have been at the expense of increasing the volume of lung irradiated to 20 Gy. A subsequent 9 Gy boost was then administered using the same bolus technique. As expected,

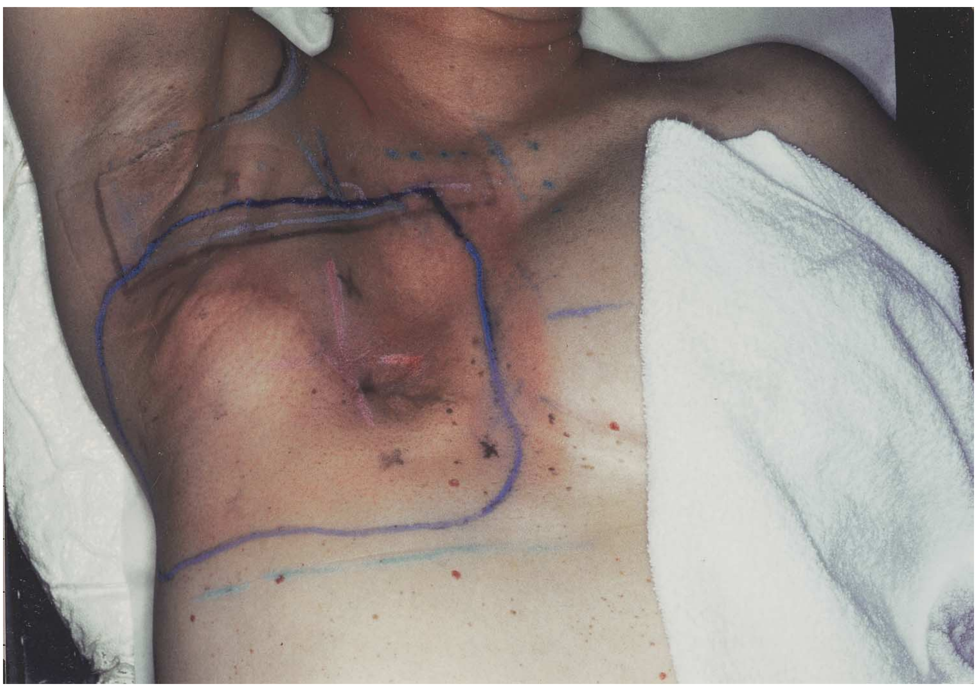


Fig. 3. View of the postmastectomy chest wall demonstrating variation in chest wall anatomy. Note the inferior medial concavity (at the base of the postmastectomy scar) and the superior lateral convexity (at the apex of the postmastectomy scar). Outlined on the patient chest wall are the treatment field for chest wall electrons and the corresponding supraclavicular/axillary apex field. Field junctions were moved 0.5 cm twice during treatment to avoid excessive dose.

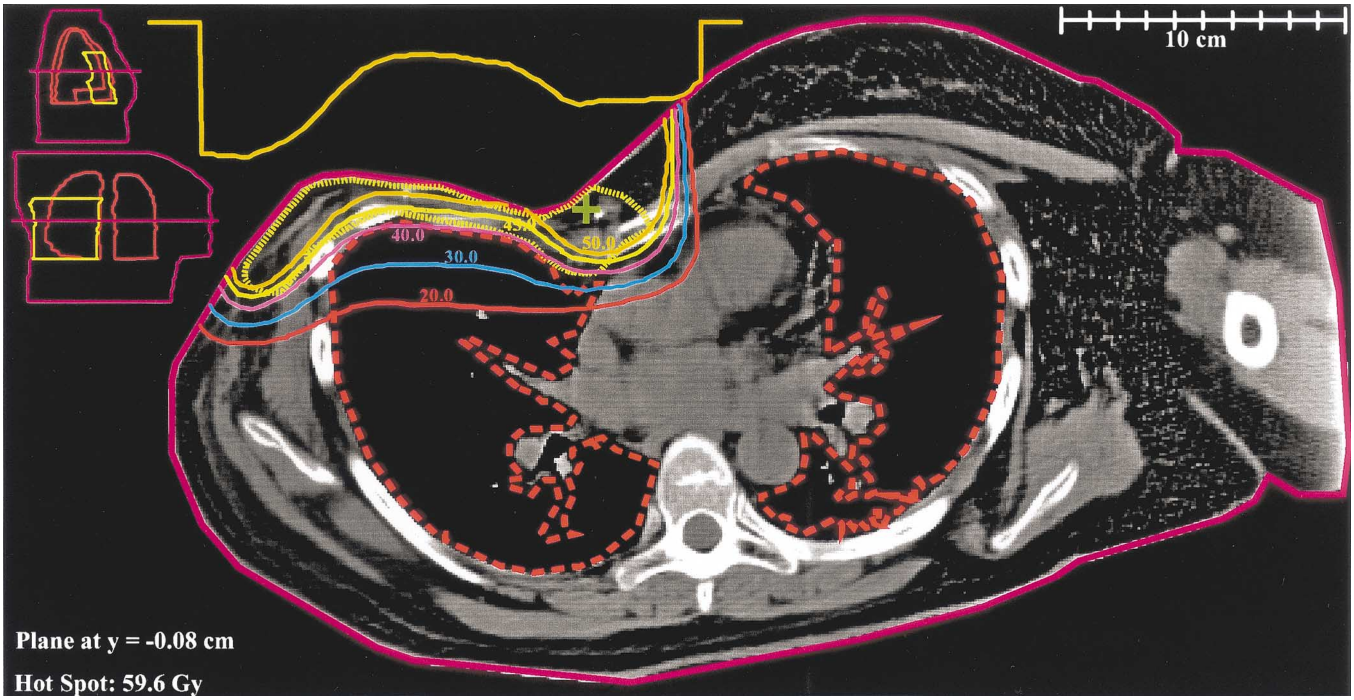


Fig. 4. Isodose distributions (Gy) using the custom 3D electron bolus for a patient with suboptimal chest wall anatomy (see Figs. 1–3). The treatment volume is shown here outlined in yellow and was treated to 45.9 Gy prescribed to 90% of given dose using 16-MeV electrons. A significantly smaller volume of lung receives irradiation using this technique. The use of wide tangents would necessitate irradiating the contralateral breast. The use of an IMC field and tangents would necessitate irradiating up to 50% of the ipsilateral lung to encompass the chest wall deformity.

the patient had brisk erythema and patchy moist desquamation but was able to complete treatment without interruption.

The second case demonstrates the usefulness of the 3D custom bolus in compensating for suboptimal location of the disease site. The patient was 37 years old and had undergone mastectomy and 4 cycles of postoperative doxorubicin and cytoxan chemotherapy for a stage T2N0 M0 right breast infiltrating ductal carcinoma presenting in the right lower inner quadrant 2 years before her presentation at M. D. Anderson Cancer Center. She was without evidence of disease until just before presentation when she noted new onset of right chest wall pain and a mass in the right medial parasternal area. A 1.5-cm firm nodule was noted at the right parasternal area medial to her mastectomy scar on examination. CT images showed a lesion in the right IMC area with extension into the right chest wall soft tissues and destruction of the sternum and adjacent rib (Fig. 5). No other abnormalities were noted. A fine needle aspirate confirmed recurrent carcinoma. No other evidence of disease was found.

The patient then received seven cycles of paclitaxel chemotherapy with a good partial response and was referred for radiation therapy. Standard tangent fields with a tilted electron IMC field (0.7-cm overlap with medial tangent field), as shown in Figure 6, would have resulted in a cold region at the site of recurrent disease (under the junction). The dose in the overlap region is also highly dependent on the precision of the field placement. Standard chest wall electrons also would have placed one or more junctions in areas of gross disease. The use of “wide tangent” fields to cover both the IMC and chest wall disease would have necessitated treatment of approximately 50% of the underlying lung. Therefore, the 3D custom bolus technique was used. She was treated to 50 Gy in 2 Gy daily fractions with 16-MeV electrons prescribed to 100% of the given dose. Field reductions were made, and an additional 16 Gy was delivered in 2 Gy daily fractions using 16-MeV electrons and the 3D bolus technique. Again, erythema and moist patchy desquamation were noted; no treatment interruption was necessary. The resulting dose distribution in an axial plane (for the first 50 Gy) is shown in Figure 7. Before treatment, the patient was CT-scanned with the custom bolus in place to verify the delivered dose. Figure 8 shows the same dose distribution calculated using the CT scan with bolus in place, and the dose coverage is almost exactly the same, as expected. Figure 9 shows that the coverage of the PTV is better for the electron bolus plan, at the expense of more dose to the right lung and heart. Of note, both patients had matching supraclavicular fields as a component of treatment, and both underwent junction changes of 0.5 cm between the anterior chest wall field and the supraclavicular field twice during treatment to avoid areas of excessive dose.

DISCUSSION

There are at present well-characterized methods of delivering PMI, and these methods result in excellent local

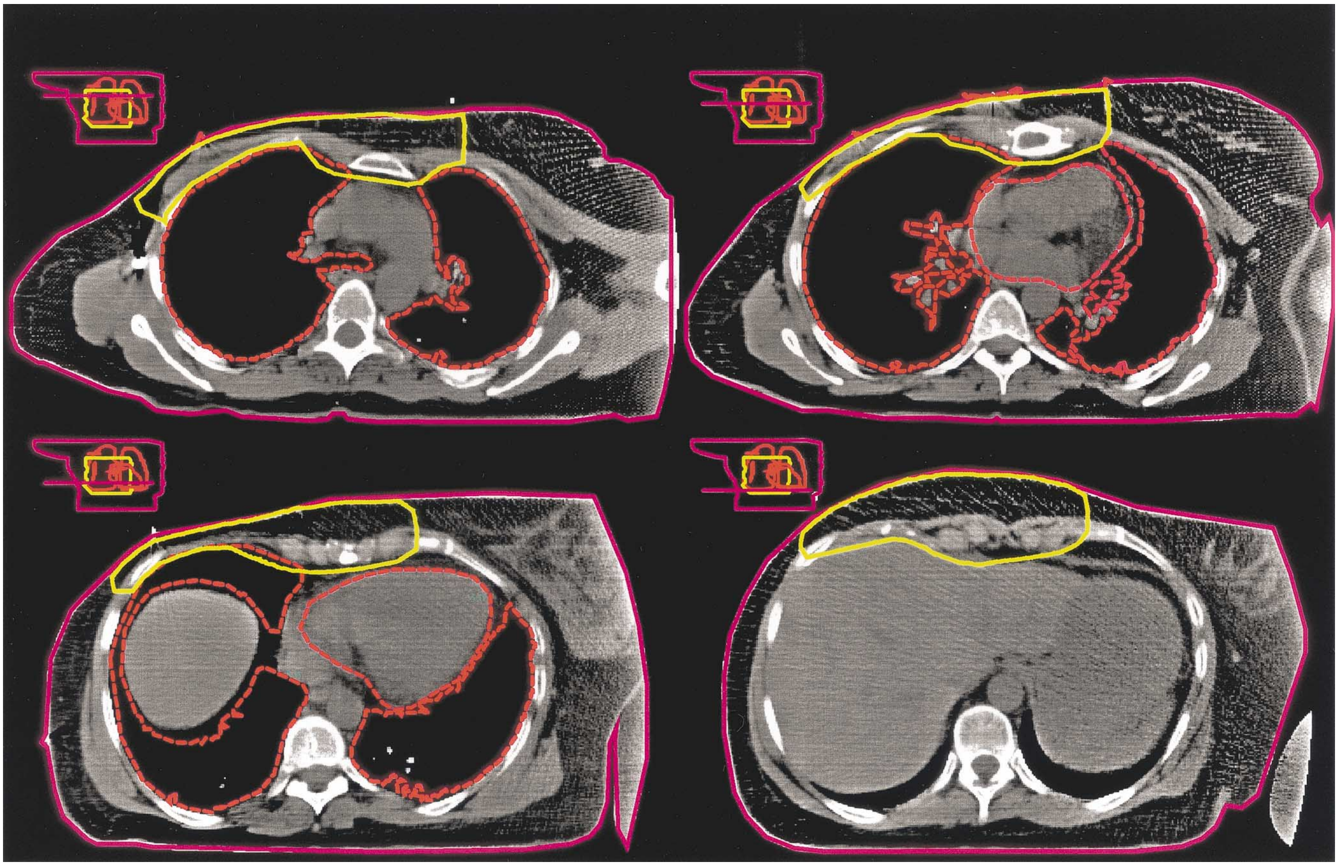


Fig. 5. Representative CT images of a patient with a lesion in the right IMC area, with extension into the chest wall soft tissues. This lesion is in an area where IMC and tangent field junctions are normally placed.

control in the majority of patients with low rates of complications (7, 8, 18–21). Further optimization of PMI through the use of wedge filters and tissue compensators is also well described. These modifications to the photon technique and the chest wall electron technique result in acceptable options for PMI for most patients; however, in some instances, such as the two index patients presented here, the usual modifications are not adequate. Conformal electron therapy using custom bolus provides a viable option in such circumstances. It also demonstrates technological advancement and innovation compared to previous chest wall electron bolus irradiation techniques. As previously mentioned, the 3D custom bolus technique uses operators that account for electron scatter and extend the bolus outside of the field to accommodate beam penumbra. Furthermore, a smooth surfaced wax bolus that does not alter the dose distribution from that planned is the end result of manufacturing the custom bolus by our technique.

Let us first consider the underlying normal tissues in considering the choice of technique for PMI delivery. It has been previously reported that large volumes of lung tissue included in the tangent fields increase the risk of pneumonitis. Lingos *et al.* reported a rate of 1–10% when tangential fields are used alone and further correlated increased pneumonitis with the use of chemotherapy (22). Hardenbergh *et al.* reported pneumonitis rates of up to 30% when irradiation was given to patients with tangent fields after undergoing dose-intensive chemotherapy and autologous bone marrow transplant (23). It is therefore very important to select treatment plans that keep underlying lung dose to a minimum. Our optimized bolus accomplishes this goal, and a significantly less volume of lung receives greater than 20 Gy, reducing the risk of pneumonitis.

The density and distribution of tissues in the chest wall also affect the treatment plan and choice of delivery. Kalef-Ezra *et al.* noted that the region of lung in proximity to the chest wall or breast had a relative electron density of almost 20% less than that of the entire lung parenchyma (24). They also noted that the electron density increased in the caudal direction in the parenchyma of the lung. Using electron beams without bolus can significantly overirradiate lung in cases where there is a considerable range in the depth of the planning volume (chest wall thickness) within a single treatment field. For every 1 cm difference, the 20-Gy dose surface could penetrate 4 cm deeper (assuming a lung density 25% that of water). Also, a 2-MeV excess in energy (e.g., using 16 MeV when only 14 MeV is needed) results in an excess penetration of the 20 Gy surface by 4 cm. Custom 3D bolus eliminates both of these potential effects. Examination of the thoracic wall also shows similar electron density variability. This variability is accounted for in the

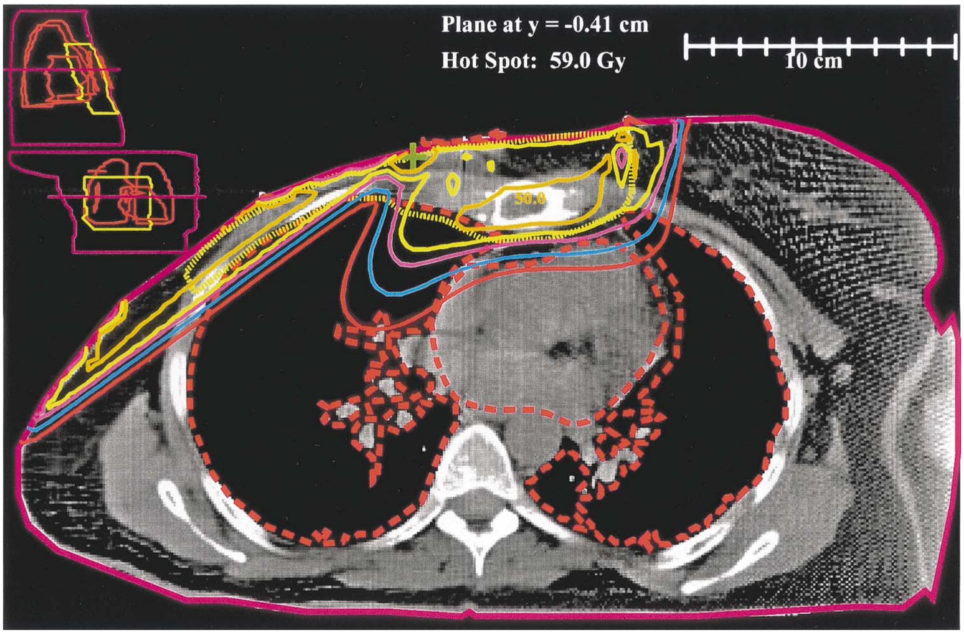


Fig. 6. Isodose distribution (Gy) using standard tangent-IMC technique for a patient with a lesion in the right IMC area, with extension into the chest wall soft tissues. The treatment volume is outlined in yellow. A dose of 50 Gy was prescribed to 100% of the given dose using 12-MeV electrons for the IMC field, and the electron-field edge was matched to the medial tangent field edge on the patient's skin surface. The 45 Gy isodose line covers the target volume, except for the cold triangle directly beneath the junction line.

3D custom technique described here as the custom bolus is designed to compensate for any tissue heterogeneity.

Another factor in selection of treatment plan and delivery is the location of the disease. For patients receiving PMI, it is preferable that no field junctions are placed in sites of recurrence (areas of gross disease), or at areas where there is a high risk for recurrence because of the resulting uncertainties in dose in the match region. One of our patient examples would have required such a junction using either the standard tangent or chest wall electron technique. In-

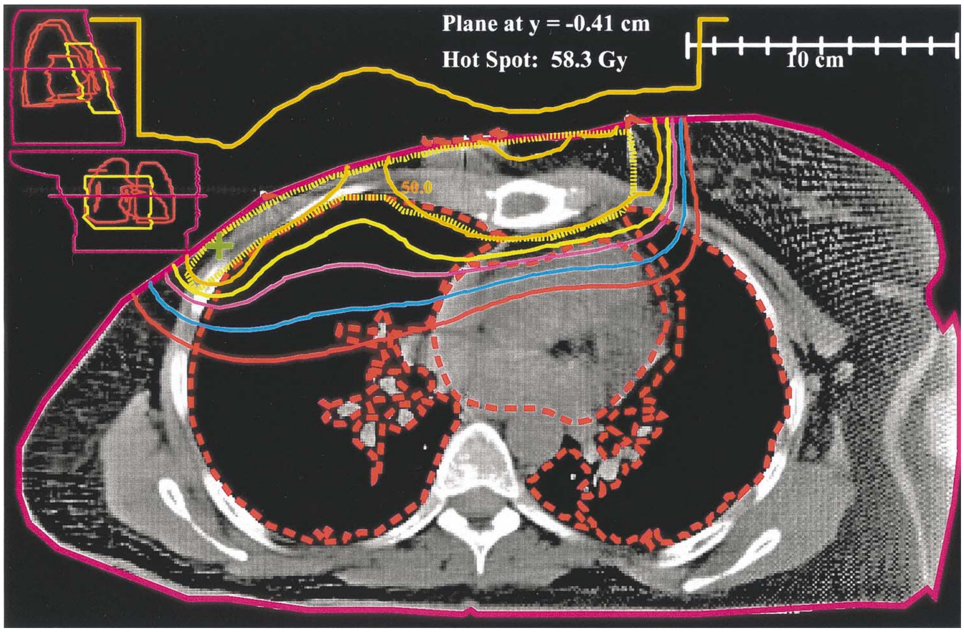


Fig. 7. Isodose distribution (Gy) using the custom 3D electron bolus technique for the same patient as in Figure 6. A dose of 50 Gy was prescribed to 100% of the given dose using 16-MeV electrons, and the bolus was designed to deliver 90% of the given dose to the target volume. The plan shows dose minimization to the ipsilateral lung and underlying cardiac tissues.

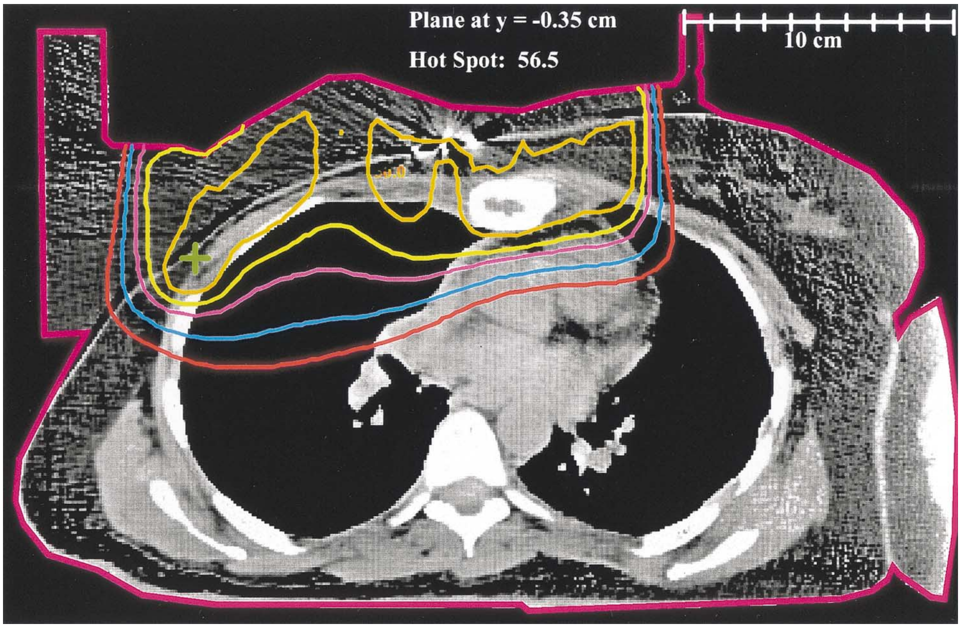


Fig. 8. Isodose distribution (Gy) using the custom 3D electron bolus technique for the same patient as in Figure 7. A dose of 50 Gy was prescribed to 100% of the given dose using 16-MeV electrons; the custom electron bolus was placed on the patient's skin and is visible in the CT image. To verify correct fabrication and positioning of the electron bolus, this dose distribution was compared to the dose distribution for the treatment plan shown in Figure 7.

stead, using the 3D electron bolus technique, there was insignificant dose gradient and no dose uncertainty across the area at risk because no field junction was required. The entire chest wall and IMC were treated with one anterior field, and making a potential treatment compromise in dose integrity in an area of high risk became unnecessary. Junctions through tumor, hot spots, or cold spots and excessive dose to underlying normal tissue would all be indicators of unacceptability and thus would result in elimination of the treatment plans and techniques producing that effect. It is

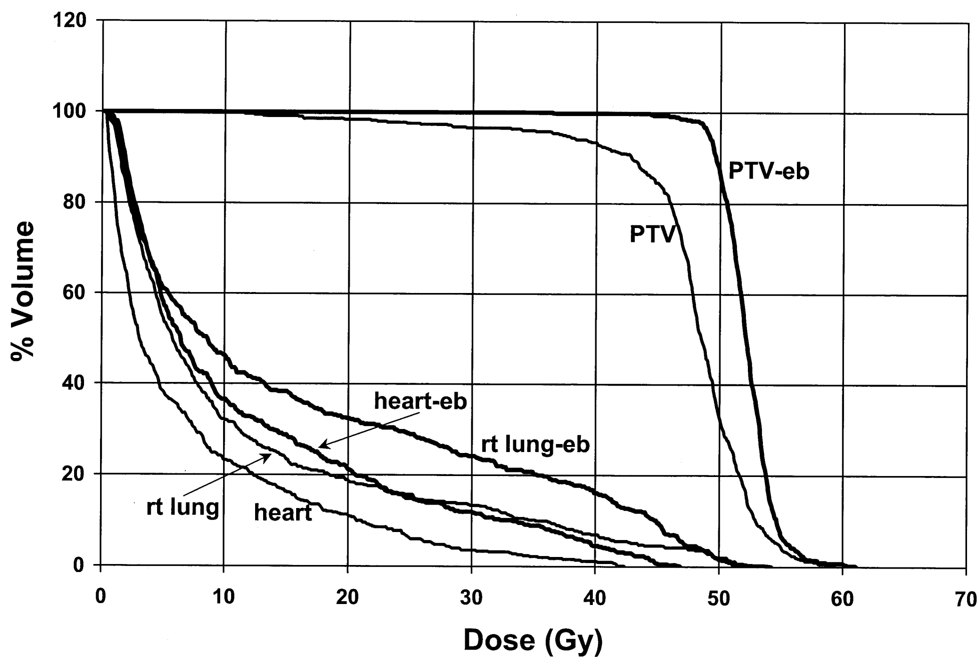


Fig. 9. Dose–volume histograms comparing the standard treatment plan (Fig. 6) to the customized electron bolus treatment plan (Fig. 7). The heavier lines (suffix –eb) are for the electron bolus treatment plan. The histograms show that the electron bolus treatment plan covers the target volume much better, at the expense of slightly more dose to the right lung and heart.

easy to see then that a technique that may be optimal for one patient may not be optimal for another. PMI delivered with the photon tangent technique or with the chest wall electron technique is adequate for most patients. However, we have also found that on some occasions neither technique is optimal and therefore another technique, such as the one presented here, is desirable.

There are however some disadvantages to this technique. Most notably, it is a labor-intensive and a time-consuming process, requiring approximately the same amount of resources as intensity-modulated radiotherapy (IMRT). Many hours are needed for manufacture and verification to provide quality assurance. Preplanning and postplanning volume CT scans must be obtained and treatment volumes must be outlined, assessed, and planned. The bolus must be verified in treatment position, and modifications may need to be made to the bolus to ensure the best possible fit. This requires additional patient visits as compared with conventional techniques and requires greater interaction between radiation oncologists, medical physicists, and support personnel.

Another disadvantage is that the skin dose is higher than that of conventional techniques. The bolus is used throughout the entire course of therapy and results in very brisk erythema as well as patchy desquamative changes. Both of our index patients experienced this; however, as previously noted, neither of the patients required treatment interruption. Patient discomfort caused by skin reaction was not severe and was managed symptomatically with healing occurring within 2 weeks of treatment completion. It is worth noting, however, that the increase in skin dose could increase the risk for telangiectasias and skin fibrosis complications, which could interfere with breast reconstruction at a later date. Long-term follow-up will be needed to further assess this potential risk as well as the traditional medical outcomes. Skin reactions are the greatest known concern with this technique. It is reassuring that none of our patients required treatment interruption. This technique, at the present time, is best reserved for specific situations where standard PMI techniques would be unsatisfactory. Improvements in decreasing bolus fabrication time may make this technique more clinically applicable.

Lastly, the software for designing the electron bolus is not available in any commercial treatment planning system, although vendors could easily implement it. Until vendors feel that there is sufficient physician demand for customized electron bolus, it is unlikely to be added to the feature list. However, with modern computer networks and standardized data exchange methods, it may be possible to design and fabricate these devices remotely, with local physicists doing the final quality assurance using their standard treatment planning software and techniques.

In conclusion, we have described an alternative technique for delivery of PMI with electrons in clinical situations where standard radiation techniques result in unacceptable results. The 3D custom electron bolus provides a conformal dose distribution, reduces dose heterogeneity, and minimizes normal tissue exposure. In patients with chest wall irregularities, this technique compensates for tissue variability. In patients with at-risk areas in inopportune locations, this technique obviates the need for matching junctions through disease. Representing another option with acceptable outcome, the 3D custom bolus is a method of optimizing PMI in settings where it may not have otherwise been delivered. Further use and long-term follow-up will elucidate the extent of late skin changes and other possible sequelae.

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