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Dosimetry and techniques for simultaneous hyperthermia and external beam radiation therapy

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An increased biological effect is realized when hyperthermia and radiation therapy are combined simultaneously. To take advantage of this effect, techniques have been developed that combine existing hyperthermia devices with a linear accelerator. This allows concomitant delivery of either ultrasound or microwave hyperthermia with photon radiation therapy. Two techniques have been used clinically: the orthogonal technique, in which the microwave or ultrasound beam and the radiation beam are orthogonal to one another, and the en face technique, in which the ultrasound or microwave beam and the radiation beam travel into the tumour through the same treatment window. The en face technique has necessitated the development of special attachments so that the hyperthermia device can be mounted to the linear accelerator and so that non-uniform portions of the hyperthermia device can be removed from the radiation beam. For microwave therapy, applicators are mounted onto the linear accelerator using the compensating filter tray holder. For ultrasound, special reflector devices are mounted to a frame that is mounted onto the compensating filter tray holder of the linear accelerator. Because the linear accelerator is an isocentric device, the height of the radiation source is fixed, and this has necessitated specially designed devices so that the ultrasound support system is compatible with the linear accelerator. The treatment setups for both the en face technique and the orthogonal technique require the interaction of both hyperthermia and radiation therapy personnel and equipment. The dosimetry and day-to-day operations for each technique are unique. The simulation for the en face technique is much different from the simulation of a normal radiation treatment and requires the presence of a hyperthermia physicist. Also, for the en face technique, the attenuation of the microwave applicator and the thickness and attenuation of the ultrasound reflector system are taken into account for radiation dosimetry. This paper presents details of the dosimetry and logistics of the techniques for simultaneous thermoradiotherapy based on 7 years of experience treating more than 50 patients.

Key words: Simultaneous hyperthermia, ultrasound, microwave hyperthermia.

1. Introduction

To take advantage of an increased radiosensitization (Overgaard 1980, Dewey 1994), radiation and hyperthermia treatments have been delivered simultaneously since 1992 at Washington University. In these procedures, the radiation is delivered midway through a 1 h hyperthermia treatment without interruption of the heating. To combine the two modalities simultaneously, it is necessary to determine tech-

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niques and dosimetry that allow the accurate delivery of both modalities. Several papers have been published describing different techniques of delivering the two modalities simultaneously. Initially, these treatments were all performed using both microwaves (using Clini-Therm Waveguide Applicators) and ultrasound (Sonotherm 1000) on a ^{60}CO unit (Moros *et al.* 1995, Straube *et al.* 1996, Myerson *et al.* 1999). Initial papers described the techniques and modifications to devices, as well as interference measurements with a ^{60}CO unit, but they did not go into detail about the day-to-day procedures necessary to ensure safe and effective treatment when combining the two modalities. Furthermore, since 1995, all of the treatments have been performed on a 6 MV medical linear accelerator (Clinac 6 and Clinac 600 c/d, Varian Associates). The transfer to a linear accelerator has necessitated some additional developments that have yet to be reported.

As described in earlier works (Moros *et al.* 1995, Straube *et al.* 1996, Myerson *et al.* 1999), two approaches have been used to deliver simultaneous hyperthermia and radiation therapy: an en face and an orthogonal technique. Briefly, the en face approach is used when both the hyperthermia and the radiation therapy will pass through the same treatment window. Because hyperthermia is always delivered to a tumour en face, this is used when the radiation is also delivered en face. In a second approach, the direction of propagation of the radiation and the hyperthermia beam (ultrasound or microwave radiation) are orthogonal to one another. In this case, the hyperthermia is still delivered en face, but the radiation beam or beams are delivered tangentially. This approach is used mostly for chest wall and breast lesions, for which the radiation portals are tangential to the treatment area. Each approach has a different set of procedures and dosimetry associated with it. This paper summarizes the techniques and dosimetry for simultaneous thermoradiotherapy delivered with a linear accelerator, and describes in detail the day-to-day procedures that are performed for those interested in performing these types of treatments. Each of the above mentioned approaches are presented separately.

2. Materials and methods

Radiation treatments in this paper were performed on a Clinac 600 c/d linear accelerator (Varian, California). This accelerator is an isocentric machine with asymetric jaws and dynamic wedge capabilities. Interference testing has been performed for this device in the presence of ultrasound (Sonotherm 1000, Labthermics Technologies, Champaign, IL) and microwave (915 MHz, CliniTherm Waveguide Applicators) fields in the same manner as previously reported (Moros *et al.* 1995, Straube *et al.* 1996), and all of the capabilities of the linear accelerator were found to be maintained, including the dynamic operation. Any department wishing to duplicate this type of set-up should repeat these types of measurement, since locations of electronics and leakage of individual systems may differ. All of the treatment set-ups are simulated on a Ximatron CX radiation therapy simulator (Varian-tem Ltd.). It is not necessary to power any ultrasound or microwave beams during the simulation. The hyperthermia treatments are performed with a commercial ultrasound system (Sonotherm 1000, Labthermics Technologies, Champaign, IL), and a commercial microwave system (Clinitherm Mark VI). The thermometry systems that are used with these devices, a thermocouple system (LT 100 Labthermics Technologies, Champaign, IL) and a fibreoptic system (Luxtron 3000, Luxtron, California) have not shown any compatibility problems while working in conjunction with the linear accelerator (Straube *et al.* 1997).

2.1. *En-face set up*

In this approach, the radiation beam travels through the hyperthermia device, whether it is an ultrasound reflector system or a microwave applicator. The microwave applicators used in the clinic are metal, air-filled, waveguide-type applicators. They present a metal surface to the radiation beam that can be as thick as 1 cm. At the patient surface, the microwave applicator is coupled to the patient via a semi-rigid mineral oil bolus. In the case of a curved surface or a setup which is not parallel to the patients surface the bolus thickness is not altered. This means that in some cases there could be an air gap between the patient and the mineral oil bolus. The effect of the air gap can be evaluated from a radiation dosimetric standpoint by looking at the varying SSD over the treatment surface.

The microwave applicator is attached to a blocking tray, which is then attached to a compensating filter tray via an aluminum frame (figure 1). On the ^{60}CO machine, the applicator was mounted to the blocking tray on which blocks then had to be mounted when the physician wanted to block a portion of the field. The microwave applicators have been mounted such that the patient/microwave applicator interface falls at a Source to Skin Distance (SSD) of 101.5 cm. The applicator itself is set up to end at 100 cm SSD and the bolus material adds another 1.5 cm of

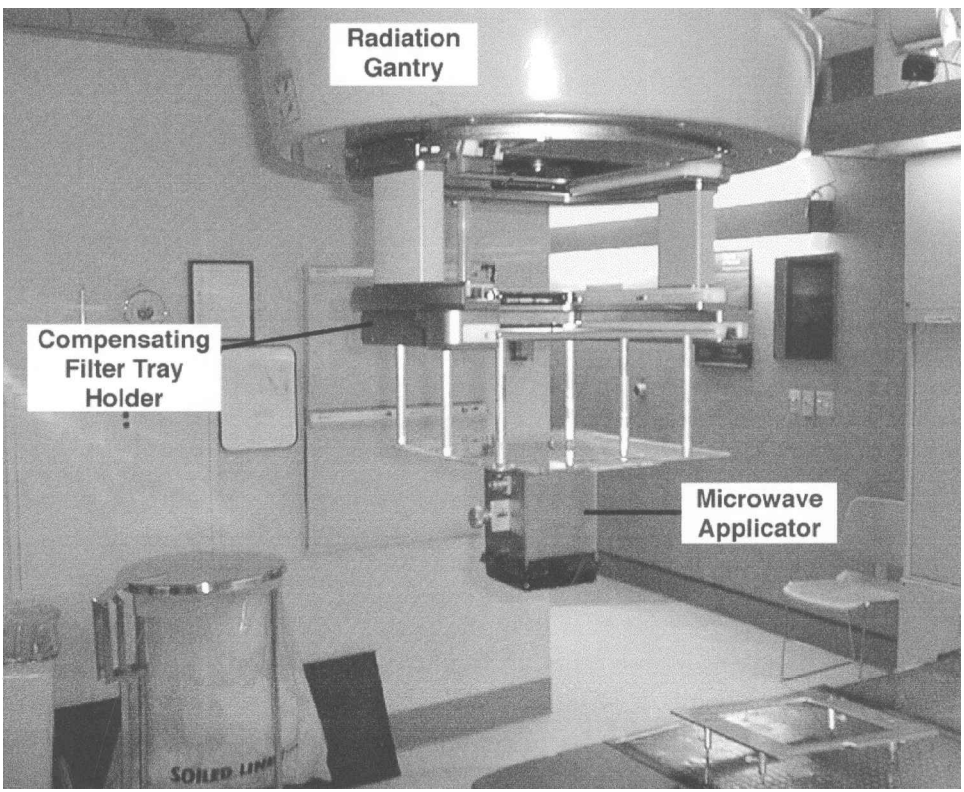

Figure 1. A Clinitherm $10 \times 10\,cm^2$ applicator mounted to a blocking tray that is mounted to a compensating filter tray via an aluminum frame. The SSD at the bottom of the applicator is 100 cm and 101.5 cm at the patient microwave bolus interface. The compensating filter tray holder is used to attach the applicator to the gantry, to ensure reproducibility, and to eliminate problems with blocking radiation fields.

water equivalent material. This is not adjustable for the microwave devices. By using the compensating filter tray holder, reproducibility of the set-up has been ensured and any interference with positioning or mounting of custom blocks eliminated.

For the ultrasound devices, the SSD can be variable, depending on the distance that achieves optimal ultrasonic coupling. As described in an earlier publication (Straube *et al*. 1996), simultaneous en face ultrasound hyperthermia uses a reflector system that is mounted to a blocking tray. The blocking tray is then mounted to a compensating filter tray via an aluminum frame (figure 2). The frame in this case is very long, and the SSDs for this device can vary from 120–125 cm for one reflector system (for a $14 \times 14\,cm^2$ hyperthermia field) and 125–130 cm for another reflector system (for a $7 \times 7\,cm^2$ hyperthermia field). These SSD's are extended because the linear accelerator is an isocentric device. The patient is, therefore, raised into the treatment position rather than the gantry being lowered to the desired position as was the case with the ^{60}CO unit. Since the ultrasound applicator must be coupled to the reflector system using the support arm of the Sonotherm 1000 (Straube *et al*. 1996), it is required that the reflector system be at a level that the ultrasound support system can reach.

2.1.1. *Dosimetry*. The maximum radiation field size permissible for the en face technique was determined by taking a film with the applicator in place. The largest

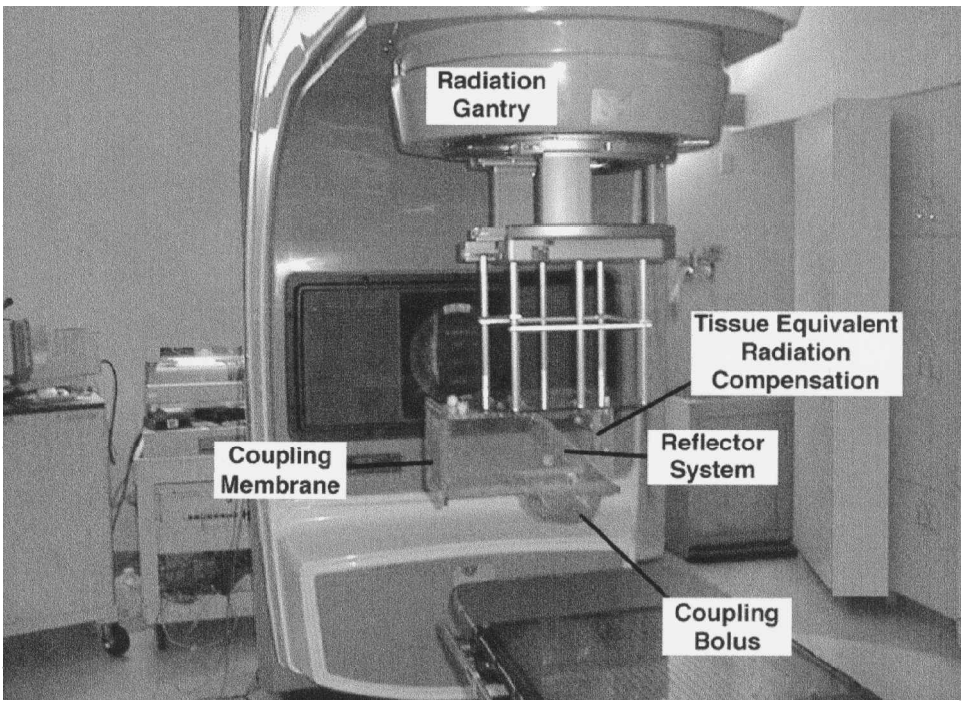

Figure 2. A reflector system for the Sonotherm 1000, 16-element applicator is mounted to a blocking tray that is mounted to a compensating filter tray via an aluminum frame. The SSD at the bottom of the applicator is variable because of the compressibility of the water bolus. The SSD ranges from 120–135 cm depending on the ultrasound applicator used and the coupling attained. The SSD is extended in order to allow coupling of the ultrasound applicator, which is supported by the Sonotherm 1000 support system.

field size measured at the surface of a water-equivalent phantom, the borders of which were contained within the microwave applicator or the reflector system (and within the border of the coupling bolus), was deemed as the largest field size usable with that applicator and has not changed since previous reports on the ^{60}CO machine (Moros *et al.* 1995, Straube *et al.* 1996). Note that this field size has nothing to do with the heating field of the applicator, but only has to do with the homogeneously perturbing portions of the applicator. Table 1 lists the dimensions of the applicators for microwaves, the reflector system for ultrasound, and the maximum radiation field size usable with each of these. The appropriateness of the applicator in terms of its ability to heat a tumour is determined based on the applicators 25% iso-SAR (specific absorption rate) contour (Myerson *et al.* 1990). The dimensions of these 25% iso-SAR contours of the applicators (Straube *et al.* 1990, Moros *et al.* 1993) are included in the table for reference.

For microwaves, the thickness of bolus and distance to the patient's surface for the applicators is well defined by the semi-rigidity of the mineral oil bolus and the mounting of the applicator to the gantry. A thin ($\leq$1 mm) circulating water bolus is introduced between the applicator and the patient if cooling is deemed necessary by the physician (Moros *et al.* 1995). The attenuation of the microwave applicator bolus set-up is measured for a single SSD, and a correction factor is generated for each applicator. This correction factor is used for dose calculation. As long as the SSD is maintained from treatment to treatment the amount of attenuating material remains the same. Appendix 1 shows the calculation procedure for microwave applicators.

The ultrasound bolus is very much compressible, and the thickness can vary from patient to patient and over the surface of a given treatment area. For this reason, dosimetry measurements had to be done for the reflector system at various SSDs. The reflector system contains water or water equivalent materials (except for a thin (< 1 mm) brass reflector) from the blocking tray to the patient (figure 2), so, from a radiation dosimetric standpoint, the ultrasound reflector system acts as a slab of tissue with a range of thickness of 20–30 cm. A correction for the Tissue Air Ratio (TAR) for the linear accelerator can then be used to calculate the dose in patients, by assuming the applicator is additional tissue overlaying the prescription point. The correction factor for the TAR factor is measured by measuring the transmission through the applicator and comparing this with the TAR measurement at a given depth in phantom. The SSD of the patient set-up then determines the amount of tissue used in the TAR table with the previously found correction factor. The measurements were done using a Solid Water phantom. Appendix 2 shows the calculation protocol for the reflector systems. Included is a table that shows the adjusted TARs when the applicator is in place.

Table 1. The maximum radiation field size allowable for the hyperthermia device listed.

	Maximum radiation field size at surface (cm^2)	Dimensions of 25% Iso Sar contour at 1 cm depth (cm^2)
Microwave applicator (cm^2)		
10×10	10×7.4	9×9
15×15	14.8×7.4	10×10.5
Ultrasound reflector system (cm^2)		
15×15	13×13	13.8×13.8
8×8	7×7	6.0×6.0

2.1.2. *Simulation*. The simulation process is significantly altered when setting up for an en face simultaneous treatment. Because the SSD, field size, and patient position must take into account the hyperthermia device as well as the irradiation set-up, it is necessary for a hyperthermia physicist to be present during the simulation procedure. Since the simulator does not have a compensating filter tray holder, a special attachment that will allow the hyperthermia device to be inserted into the blocking tray and maintain the device's distance from the radiation source is used. The field size at the skin must be less than or equal to the maximum field size allowable for the given hyperthermia device. The field is aligned, the applicator is placed into the simulator blocking tray holder, and the SSD is adjusted until the ultrasonic coupling is considered to be optimal. This SSD is then recorded for use during treatments and calculations. When ultrasound is used the SSD will change under the bolus of the applicator because the ultrasound bolus acts as a box bolus type compensator. The simulation field is then radiographed. Filming has been attempted with the hyperthermia device in place on the simulator, but, because the device contains metal (microwave waveguide or ultrasonic reflector [< 1 mm brass plate]), the ability to transmit through the devices is limited with the low energy of the simulator x-rays. Figure 3 shows the ultrasound reflector system attached to the simulator gantry. Blocks can be used as desired, since they

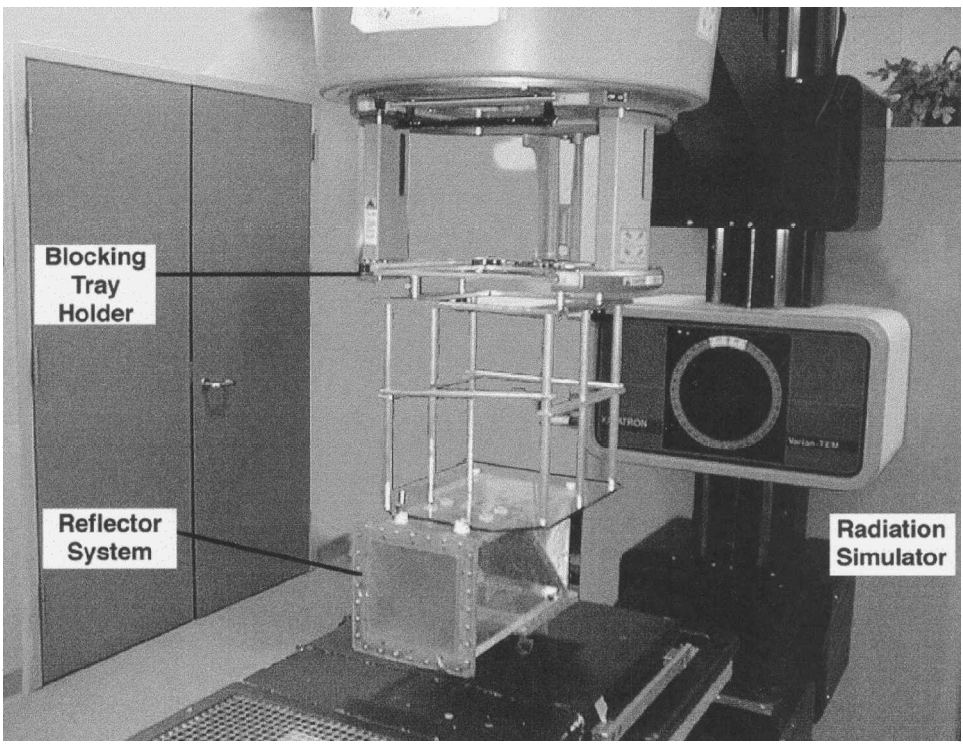

Figure 3. The reflector system mounted to the gantry of the radiation simulator. A special attachment is used to insert the reflector system into the blocking tray of the simulator gantry while maintaining the same distance from the reflector system to the radiation source that is attained in the linear accelerator set-up. This set-up is used to determine the SSD that achieves optimal coupling and to ensure that the ultrasound system can be coupled to the patient effectively.

will not interact with the hyperthermia device in any way. Wedges and other compensators can also be used, although they are not usually necessary on days when hyperthermia treatments are delivered since the bolus of the hyperthermia device acts as a missing tissue compensator. On occasion, the physician desires to abut the thermoradiotherapy portal with additional radiation fields using electrons or photons. The necessary bolusing and junction shifts are done to minimize 'hot' and 'cold' radiation doses (Harms and Purdy 1991).

2.1.3. *Treatment.* In the case of microwaves, invasive thermometry is done through in dwelling plastic catheters which remain in place for the course of treatment using plastic fibreoptic thermometers. In the case of ultrasound, thermocouple probes are placed for each treatment. Probe placement is usually performed in the linear accelerator room before the treatment set-up, although placement has been performed in other areas of the department so that the linear accelerator is not tied up with the hyperthermia treatment any longer than necessary. Care must be taken when transporting the patient into the treatment position on the accelerator couch with the probes in place, and this is not advisable for patients with head and neck lesions since moving the patient could cause shifts in the needle position. The patient is set up for radiation treatment without the hyperthermia device in place initially, so that the radiation therapists can view the radiation field lines. The field is set up at the pre-determined SSD as measured in the simulator. After the radiation setup, the table height is noted, and the table is lowered slightly to allow insertion of the hyperthermia device into the compensating filter tray holder. After insertion of the device, the table is slowly raised back into the treatment position. The coupling is checked to ensure that optimal coupling is attained at the SSD determined in the simulator. A double-exposure portal verification film is taken, with the hyperthermia device in position for both exposures. The first exposure is taken with the blocked field, and the second exposure is taken with an open field. In this way, the physicist and physician can visualize the placement of the applicator and the position of the blocked field relative to the bony anatomy of the patient. It is also possible to ensure that all of the radiation beam is passing through the hyperthermia device and boluses before it enters the patient. Because the reflector system can attenuate the radiation beam by as much as 50%, it is important to make sure that all of the beam is contained within the device before it enters the patient to avoid overdosing tissues that lie outside the hyperthermia device's boundaries. The metal walls of the microwave applicator would attenuate a radiation beam passing through them. On the other hand, any radiation fields that lie beyond the microwave applicator or the reflector system would not be attenuated and could cause overdosing of the tissues in this region. Provided that the applicator or reflector system is set up in the reproducible manner described earlier (attached to the radiation gantry), and the field size is less than or equal to the maximum allowable, the beam will fall within the walls of the applicator or within the bolus of the reflector system. Figure 4 is a reproduction of a dual exposure portal film for a patient with the ultrasound reflector system in position for treatment. This film ensures that the entire beam travels through the applicator or reflector system. After the film is approved by the physician the hyperthermia treatment is begun. Figure 5 shows a patient set-up with the en face technique. The patient is in position for radiation treatment with the reflector system

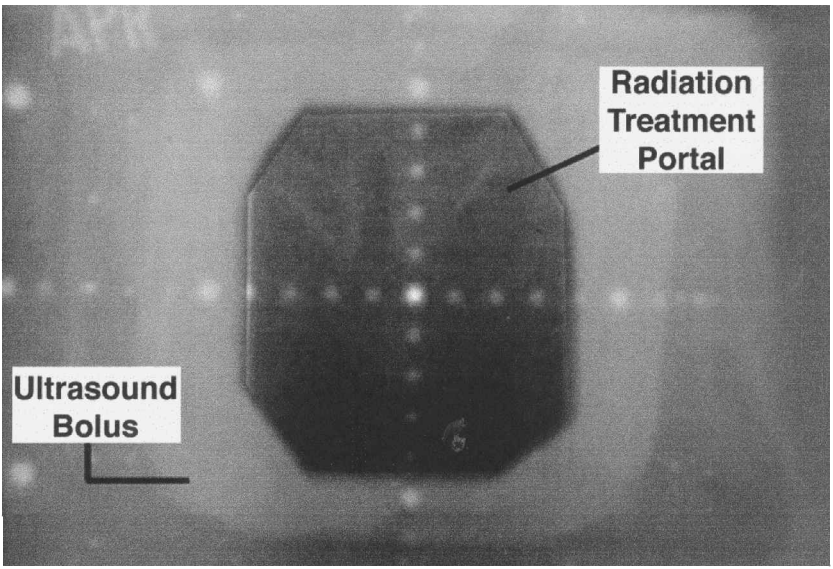

Figure 4. A portal film taken with a patient in position for an en face treatment. The portal film shows the positioning of the patient with respect to the blocked irradiation field as well as the hyperthermia device (in this case ultrasound reflector system for the 16-element Sonotherm 1000 applicator). It is also possible to visualize the hyperthermia bolus and examine the relative position of the radiation field with respect to the hyperthermia device. In this way it is possible to ensure that the entire radiation beam is contained within the hyperthermia device.

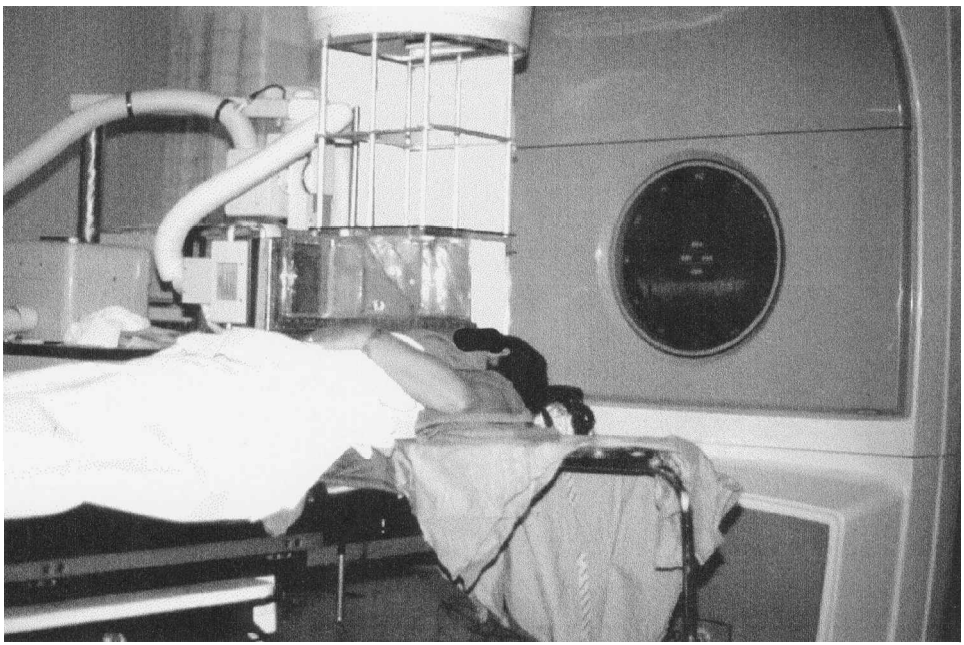

Figure 5. A patient set-up using the en face technique for the treatment of an internal mammary node. An ultrasound reflector system supported on the gantry is coupled to the patient's chest. A 16-element ultrasound applicator is shown coupled to the reflector system and being supported by the Sonotherm 1000.

mounted in the compensating tray holder of the linear accelerator. The ultrasound generating system is to the right side of the patient and the ultrasound applicator is coupled to the reflector system.

2.2. *Orthogonal approach*

2.2.1. *Simulation.* The simulation procedure is not changed much from a normal radiation treatment simulation. The most important aspect is to make sure that the set-up of the radiation beam is compatible with the administration of the hyperthermia. For the orthogonal technique, parallel opposed fields are frequently used for radiation therapy. The gantry angle of the radiation beam must be such that the angle can be achieved by the hyperthermia device while still maintaining adequate coupling of the hyperthermia device. It is desirable, in the case of parallel opposed fields, to treat both radiation fields with the hyperthermia device in place. In order to be able to rotate the radiation gantry without moving the patient, it is necessary to use a centralized source to axis-of-rotation distance (SAD) set-up. This may cause clearance problems with the hyperthermia device, however, since the gantry will be closer to the patient, and these issues must be considered in the simulation. Also, in order to be able to rotate the gantry and treat the parallel opposed field, the hyperthermia device must be positioned such that the device's hardware is not in the way of the radiation beam for either field or in the way of the gantry during rotation. Some chest wall treatments require a table rotation so that the superior tangential field edge will align with a supraclavicular field. This must also be considered since the rotation may have to be done with the hyperthermia device in place when the second tangential or opposed field is treated. Blocks, wedges, or compensators can be used as needed for this technique. An advantage of the orthogonal technique is that any radiation field size can be used, and it is sometimes chosen when an en face set-up is not feasible because of logistics or field size limitations.

2.2.2. *Dosimetry.* The orthogonal approach generally does not perturb the radiation beam except to provide bolusing and some compensation of the radiation beam. In order to account for the effect of the applicator, the hyperthermia device can be included as an external contour in treatment plans. The bolus is represented on the contour of a patient as a 5 cm (ultrasound) or a 2 cm (microwaves) thick bolus over the area covered by the hyperthermia device. A radiation treatment plan is then created with this bolus in position for the number of hyperthermia treatments planned. In cases where the remainder of the area is bolused with layer bolus, the effect of the applicator is minimal. In cases where the hyperthermia in not used with all fractions of radiation, the bolus is scaled according to the ratio of the number of treatments concomitant with hyperthermia to the total number of radiation fractions. Figure 6 shows a treatment plan for a patient treated with the orthogonal technique with the applicator in place for four of eight radiation fractions.

2.2.3. *Treatment.* The orthogonal technique is similar to any other radiation or hyperthermia treatment, except that both are set up simultaneously. A portal film is taken of the radiation set-up before treatment, even though the radiation is not passing through the applicator. Depending on the set-up of the gantry for the orthogonal technique, it may be necessary to use a special attachment on the

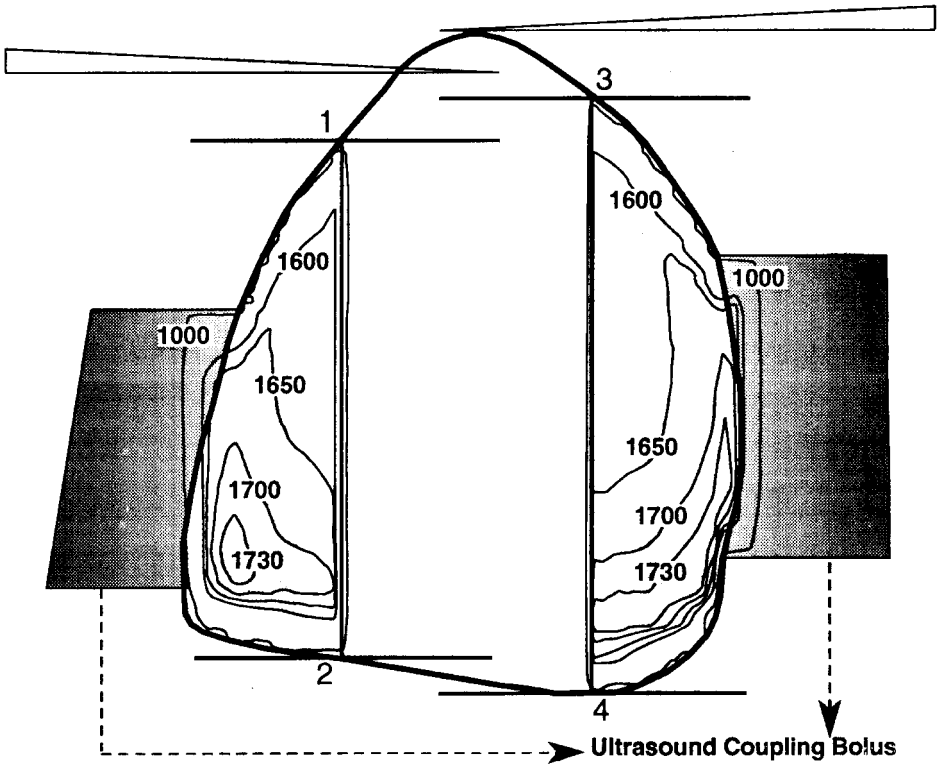

Figure 6. A two-dimensional treatment plan for a patient with bilateral neck nodes treated with simultaneous hyperthermia and irradiation for four of a total of eight radiation fractions to each side of the neck. The bolus of an ultrasound hyperthermia applicator (in this case a four-element ultrasound applicator (Sonotherm 1000, Labthermics Technologies, Champaign IL)) is externally contoured on the plan, and its effect is taken into account for the dose calculation in the plan. In this case, only the area under the applicator is bolused, and the rest of the field is left open. The radiation treatment portals are parallel opposed with wedges (shown) and centreline blocks. The beam projections are numbered 1–4 and are shown on the figure. Radiation isodose curves are labelled in cGy.

ultrasound device. For instance, in cases when the radiation beam is coming from a lateral approach and the ultrasound beam is coming from an anterior-posterior approach, a brass reflector is used so that the applicator can be rotated to a position that will allow the bolus to approach the treatment area (figure 7). The reflector is necessary because of the height mismatch of the ultrasound applicator support system and the gantry of the accelerator. Patients set up on the accelerator table are too high off the floor to be coupled with the ultrasound device as it is normally used, especially for a SAD setup. The reflector is attached directly to the applicator and can be used as the applicator is normally used. Layer radiation bolus is often used for orthogonal set-ups, and in these cases the bolus is placed around the microwave or ultrasound applicator to cover areas of the radiation field that are not being bolussed by the hyperthermia device. When possible, the gantry is rotated to treat the parallel opposed field with the applicator in place. Another film is taken before irradiating this second field to ensure that the radia-

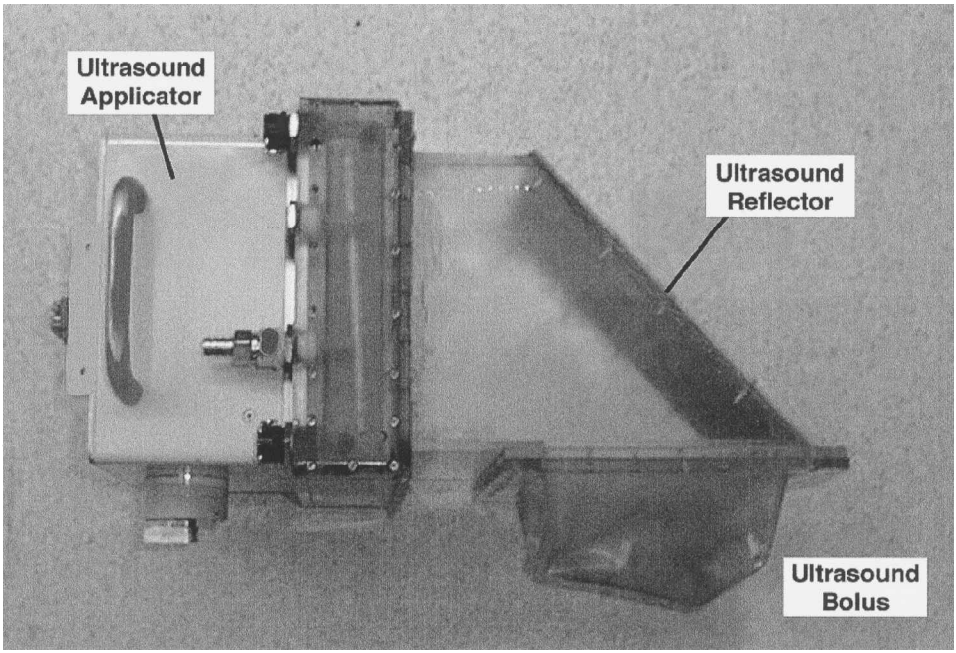

Figure 7. A photograph of the 16-element ultrasound applicator (Sonotherm 1000, Labthermics Technologies, Champaign, IL) with a reflector attached to the applicator. The reflector is necessary in some cases when the orthogonal technique is used because of the height mismatch between the position of the patient for radiation therapy and the support system for the Sonotherm 1000.

tion is not passing through the applicator or any other hardware of the hyperthermia system prior to entering the patient's tissue. Figure 8 shows the set-up of a patient treated with the orthogonal technique, which required the attached reflector.

3. Discussion

To date, over 50 patients have been treated with ultrasound and microwave hyperthermia simultaneously, with photon radiation therapy delivered by either a ^{60}CO unit or a 6 MV linear accelerator. The clinical results of two successive protocols are presented in a paper by Myerson *et al.* (1999). The authors have been able to develop techniques and devices that make it possible to deliver the two modalities simultaneously. These techniques and devices continue to be refined in terms of dosimetry and mechanical compatibility. Developments are underway for an improved method of delivering orthogonal hyperthermia with chest wall tangents which will consistently allow rotation of the gantry from the medial to the lateral tangential (or vice versa) without interfering with the hyperthermia and which will allow clearance by the radiation gantry. The size and height of the Sonotherm 1000 support system is a hindrance for this purpose because it was not designed specifically for simultaneous radiation and hyperthermia. New devices currently under development will not be limited in this way. These devices are being developed to be compatible with electron or photon radiation therapy and will allow patients to be treated with simultaneous ultrasound hyperthermia and electron therapy (Moros *et al.* 1998). They will also be lower profile and

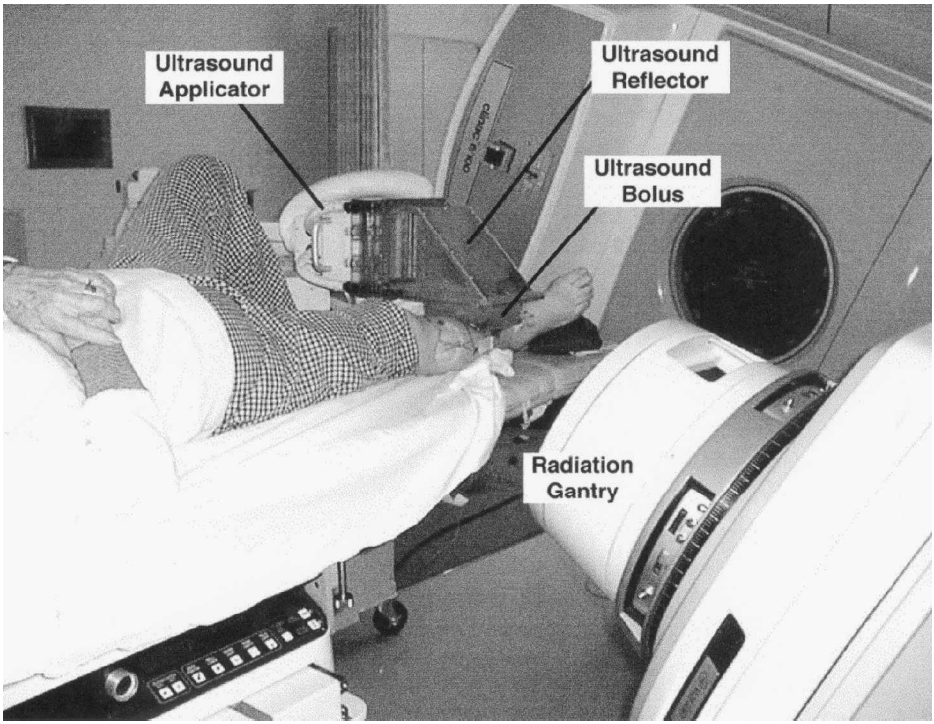

Figure 8. A patient is set up for the orthogonal technique. The patient is receiving tangential irradiation with concomitant hyperthermia to the lower leg. The reflector is attached to a 16-element ultrasound applicator in order to achieve the required height to couple the ultrasound to the patient's leg while the patient is in position for radiation therapy.

less bulky, which should simplify the set-up and dosimetry for simultaneous thermoradiotherapy.

Acknowledgements

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Appendix 1

Calculation technique for simultaneous small microwave hyperthermia and Clinac-6 irradiation

The microwave (MW) applicators have been tested for dosimetric characteristics on the Clinac 6 at JH. The applicators are in the process of being placed on extended rails. This will place the end of the applicators at 100 cm from the source. In addition, the applicators will not be attached to the blocking tray, instead they will be suspended from the compensating filter rail. Therefore, blocking can be accomplished from the blocking tray allowing ease of custom blocking. There is additional mineral oil and water bolus that is 1.5 cm in total water equivalent thickness. The treatment distance will, therefore, be 100 cm to end of applicators and 101.5 cm to the patient surface. This will place the typical prescription distance (patient surface) at the depth of the $d_{\max}$. The calculation will by simply the standard SSD calculation method with the exception of the applicator transmission factor. If the prescription depth is anything deeper than $d_{\max}$ (5 cm effective depth), the per cent depth dose (PDD) will be calculated for the depth below surface plus 1.5 cm. The dose in Free Space (D_{fs}) and Peak Scatter Factor (PSF) will simply use the collimator setting and effective blocked field sizes respectively.

$$MU = \frac{TD}{PDD(1.5 + \text{depth under surface, EFS}),\ PSF(\text{EFS}),\ DFS(\text{CFS})ATF}$$

where EFS = effective field size; CFS = collimator field size; and ATF = applicator transmission factor.

The transmission factors for the MW applicators were measured with the Capintec PS-033 parallel-plate ionization chamber. The 'open' readings were taken for the MW field size at 100 cm SSD, and 101.5 cm source to chamber distance under 1.5 cm of solid water. The MW transmission measurements were taken with the applicator in place with the distal surface at 100 cm (with an additional tray attached), the mineral oil and water bolus and the chamber at 101.5 cm.

An additional measurement was performed to verify the calculation method. After establishing a dose per NC factor for the dosimetry system (Capintec + Keithley), the 10×10 applicator and boluses were placed on top of the solid water phantom with the chamber placed at 3.0 cm below the surface. The measured dose for 200 MU was 135.0 cGy. The expected dose using the

above calculation algorithm (with the *PDD* calculated for a depth of 4.5 cm) was 134.6 cGy.

Fixed parameters

SSD = 100.0 cm (source to bottom of applicator); Prescription depth = 1.5 cm bolus + depth under surface. For $15 \times 15\,cm^2$ MW applicator; attenuation factor = 0.816; *Maximum collimator field size* = $14.8 \times 11.9\,cm^2$. For $10 \times 10\,cm^2$ MW applicator; attenuation factor = *0.791*; *Maximum collimator field size* = $10.0 \times 7.4\,cm^2$

Appendix 2

Calculation technique for simultaneous large ultrasound hyperthermia and 600C/D irradiation

Parameters

SSD + d = 121 cm to 130 cm; field size = 7 cm × 7 cm to 13 cm × 13 cm at depth; source-to-top of applicator distance = 100 cm; and correction to nominal TAR = 1.008.

The ultrasound applicator has a pliable membrane that conforms to the patient surface to allow the ultrasound to transfer from the water reservoir to the patient tissues. The water reservoir presents a wedge-shaped attenuation path prior to the pliable portion of the applicator. There is a water-filled widge-shaped insert that must be attached to the applicator to compensate for its shape. It is critical that this piece be in place during treatment or the dose distribution will suffer. As there is no radiation safety interlock on the device, visual and radiological confirmation must be performed prior to treatment. The radiological conformation (portal film) will also assure that the applicator is correctly positioned relative to the radiation beam.

Because the membrane is pliable, the amount of water between the source and the patient is a function of the patient *SSD*. The monitor unit calculation is, therefore, also a function of *SSD*. The calculation protocol is:

$$MU = \frac{TD(cGy)}{TAR_{\mathrm{UHL}}(SSD + d, FS_{\mathrm{eff}}) \times D_{\mathrm{fs@101.5\,cm}}(CS) \times \left(\frac{101.5}{SSD + d}\right)^2}$$

$$GD = TD\left(\frac{SSD + d}{SSD + 1.5}\right)^2 \times \frac{TAR_{\mathrm{UHL}}(SSD + 1.5)}{TAR_{\mathrm{UHL}}(SSD + d)}$$

where the *SSD* is defined at the central axis, d is the prescription depth, FS_{eff} is the blocked field size at $SSD + d$, and *CS* is the collimator setting. Interpolate TAR_{UHL} as appropriate. If the dose is prescribed to a depth shallower than 1.5 cm, the given dose is equal to the tumour dose. The TAR_{UHL} is a TAR only for the large ultrasound hyperthermia applicator and is determined from the Clinac-6 TAR table with an additional correction factor of 1.008 to account for scattered radiation. The TAR table requires that the distance from the source to the top of the large ultrasound hyperthermia applicator is 100.0 cm.

Calculation example:

TAR_{UHL}	Blocked field size at prescription point						
$SSD + d$ (cm)	7×7	8×8	9×9	10×10	11×11	12×12	13×13
120	0.490	0.500	0.506	0.523	0.532	0.543	0.550
121	0.469	0.479	0.488	0.501	0.510	0.521	0.529
122	0.447	0.457	0.469	0.479	0.490	0.499	0.507
123	0.427	0.437	0.448	0.458	0.469	0.478	0.487
124	0.406	0.416	0.428	0.437	0.447	0.456	0.465
125	0.388	0.398	0.407	0.417	0.427	0.436	0.444
126	0.369	0.379	0.388	0.397	0.406	0.414	0.422
127	0.354	0.363	0.372	0.382	0.390	0.398	0.405
128	0.339	0.348	0.358	0.366	0.373	0.382	0.389
129	0.322	0.332	0.342	0.350	0.359	0.366	0.372
130	0.306	0.316	0.326	0.335	0.344	0.350	0.357

TC = 300 cGy
Collimator setting = 8.0 cm × 8.0 cm @ 100 cm.
Blocked field size = 9.0 cm × 9.0 cm @ 125 cm.
SSD = 122 cm
Depth = 3.0 cm
SSD + d = 125.0 cm

The open field size is: 8.0 cm × 8.0 cm @ 100 cm (use this to look up the D_{fs});
The blocked field size is: 9.0 cm × 9.0 cm @ 125 cm (use this to look up $tTAR_{UHL}$).

$$\text{Time} = \frac{300\,\text{cGy}}{0.407 \times 0.958\,\text{cGy}/MU \times \left(\frac{101.5\,\text{cm}}{125.0\,\text{cm}}\right)^2} = 1150\,MU$$

$$GD = 300\left(\frac{122.0 + 3.0}{122.0 + 1.5}\right)^2 \frac{0.438}{0.407} = 330\,\text{cGy}$$