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The Berlin Extension of the Stanford Hyperthermia Treatment Planning Program

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Abstract. In the field of deep regional hyperthermia, one of the most widely used devices is the BSD-2000 Hyperthermia System which employs the Sigma 60 applicator. The Sigma 60 consists of four independent sources, giving it the potential to control the energy pattern within the patient. The independent amplitudes and phases, as well as frequency selection and applicator position, present a large number of parameters for the operator to determine. Computer simulation has long been recognized as an attractive approach to optimizing these parameters.

A treatment planning program was used in clinical practice at Stanford University Medical Center for two years. It demonstrated the feasibility of computer simulation for deep regional hyperthermia in a clinical situation. However, several parts of this system were written in a language specific to one workstation, which severely restricted the wider distribution of the program to other users of the Sigma 60.

A new treatment planning system for the BSD 2000 has been developed and put into clinical practice at the Rudolf Virchow Clinic of the Free University of Berlin. The new method, which we will refer to as the Berlin system, has a simpler model construction program and a considerably better graphics capability. However, the most important feature is that all programs are written in FORTRAN, C, or the X Window graphics system. Therefore, the entire treatment planning system is completely portable to other workstations.

Key words: Deep hyperthermia, 3D SAR modelling, treatment planning

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1 Introduction

Hyperthermia is the heating of cancer tissues to gain a therapeutic advantage. Among the most challenging problems for non-invasive hyperthermia is the heating of deep-seated tumors, such as originating from the rectum, cervix, bladder or prostate, usually referred to as deep regional hyperthermia. This is often accomplished with electromagnetic (EM) or ultrasonic energy sources. When using radio frequency (RF) electromagnetic energy, multiple sources are usually needed, because the penetration depth of one single source is strongly limited in human tissue. It is only with the use of constructive interference of several applicators that a sufficient amount of energy can be delivered to result in therapeutic heating. In clinical practice, these applicators are arranged in an annulus around the patient, a configuration known as an Annular Phased Array (APA).

One of the most widely used of this class of applicators is the Sigma 60 Applicator of the BSD 2000 Hyperthermia System (BSD Medical Corp., Salt Lake City, Utah) [11]. This applicator consists of eight dipoles grouped in four groups of two each. Each group is referred to as a quadrant. Each quadrant is powered by its own linear class A amplifier, capable of delivering up to 500 Watts of RF power in the frequency range of 60 to 120 MHz. All quadrants are powered coherently at the same frequency, but each can have a different amplitude and phase. It is this ability to drive the quadrants at different amplitudes and phases that gives it the ability to alter the energy distribution within the patient. This is done in the hope of maximizing energy distribution in the tumor area while minimizing the amount of energy delivered to normal tissue.

It has long been recognized that computer simulation could play a role in determining the input parameters for treatment in a device like the Sigma 60 [5, 12]. A system developed at Stanford University Medical Center (S3DHTP) was put into clinical use over a two year period [10]. It proved to be helpful in the treatment of patients in the Sigma 60 by aiding in preparing a treatment, in retrospectively analyzing side effects [1], and in eliminating patients for whom the treatment would be unsafe or unlikely to succeed [4]. However, it proved difficult to distribute this treatment planning to other users of the Sigma 60 because much of the essential graphics was written in language specific to the workstation being used, a Silicon Graphics IRIS 4D/240 GTX, (Silicon Graphics Corp, Mountain View, CA) [2, 3]. A new treatment planning program for the Sigma 60 has been developed which has several advantages over the Stanford program:

1. The output graphics uses the X Window System. This makes it potentially portable to virtually any UNIX based workstation.

2. There are several improvements to the output graphics.
3. The program used to create the patient model uses no graphics at all; a simple FORTRAN program creates a patient model from a 60 slice CT scan in 10 minutes.

The development of this new system will be described, along with preliminary clinical observations.

2 Procedure

Here is the basic procedure used in preparing a computer simulation of a patient treatment in the Sigma 60:

1. A 60 slice CT scan of the patient is made. The slices are taken at 1 cm interval, usually centered at the tumor site. The CT scans are used to create a model of the patient. This model consists of 0.5 cm voxels representing the tissue types at the corresponding locations [3].
2. The model forms the input to an EM simulation program [6]. This program uses the finite-difference time-domain (FDTD) method. The 0.5 cm voxels of the model are used to form 1 cm cells. The program simulates the RF radiation from one of the quadrants and its interaction with the patient model. Four such runs, corresponding to the four quadrants, are made. In a single run the complex electric fields in every 1 cm cell at every frequency of interest (usually 70, 80, and 90 MHz) are calculated simultaneously and stored [7].
3. Using the complex E fields calculated in step 2, the resulting specific absorption rate (SAR) can be determined at every cell in the patient model using the principles of superposition and linearity [7]. These results are displayed on a graphics workstation.

3 Model Creation

In running an FDTD simulation of the patient in the Sigma 60 applicator, it is necessary to have a model of the patient based on the electromagnetic properties of the tissues. For this purpose, human tissues can be divided into two basic categories: a) high-water content tissues, like muscle, and b) low-water content tissues like fat and bone. The properties are determined directly from the pixel values of the CT scans by the following mapping of Hounsfield Units (H.U.) to tissue type [3] shown in Table I:

Table I

Hounsfield Unit	Tissue Type	Tissue Number
below -900	Air	0
-900 to -130	Partial Muscle	(0-90)
-130 to 0	Fat	5
0 to 100	Muscle	98
above 100	Bone	5

By “partial muscle” it is meant that this pixel represents an average somewhere between air and muscle. The lung is the only site where this commonly occurs. After mapping to a “tissue number”, groups of pixels are averaged together to form voxels of 0.5 cm.

Contours are needed around the outer edge of the body and the tumor site. An outer contour around each CT slice is needed to mask away the patient’s clothes, the CT bed, etc. A contour around the tumor site is needed to mark the target area. These contours can be created in any manner, so long as the final result is a group of X, Y coordinates in the plane of the CT scan. (Radiation therapy treatment planning programs, available in many radiation therapy departments, almost always have such a capacity.) In the Berlin system, the program TOMAS (“tool for manual segmentation”) from the treatment planning system VOXEL-PLAN (developed at German Cancer Research Center) is used for contour generation. A program has been developed which connects the lines and fills in the contour to create a mask. Pixel values which are outside the mask are discarded and replaced with the tissue number 0, i.e. air. The tumor contour is used to identify the tumor site on the output graphics, and can be employed for subsequent optimization procedures.

Note that no special graphics are needed to create the patient model. It requires only the H.U. of the CT scans, and the X, Y coordinates representing the contours around the outside of the patient body, and those representing the tumor site. The program is written in FORTRAN. Once the CT data is stored in the computer and the contours have been created, the program to create the model takes about ten minutes.

4 FDTD Simulation

The FDTD program used to simulate a hyperthermia treatment in the Sigma 60 is similar to the one previously used [6], so a detailed description will not be given here. The entire program consists of a problem space of about 400,000

cells of 1 cm^3 each, of which 20,000 to 30,000 are the patient model, and the rest are the Sigma 60 applicator and the surrounding area. Only four runs of the program are needed to compute all the data necessary for the output stage [7]. Each computer run requires 1 hour on a SUN Sparcstation 10 workstation.

5 Output Graphics

When the model has been created and the four runs of the FDTD method corresponding to the four quadrants have been made, the SAR distribution for any set of input parameters, i.e., frequency, amplitudes, and phases, can be calculated using the principles of superposition and linearity [7]. This step requires only a few seconds on a workstation. However, because the output is approximately 25,000 numbers corresponding to the cells of the patient model, it is important that the results be displayed in a meaningful way.

In the S3DHTP, the SAR values were converted to isolines which were displayed over the patient's CT scans. The various slices were accessed by clicking the mouse of the workstation. This was found to be an excellent means of relating a potential SAR distribution to the specific anatomy of the patients [3].

The Berlin program is fundamentally the same with a few added features:

1. While viewing the SAR distribution over a CT scan, a sagittal view of the patient is shown to indicate where that slice is located (figure 1).
2. Besides the contours on the CT slices, the SAR can be viewed as a "colorwash" (figure 2). This often makes it easier to perform qualitative comparisons of the SAR distributions.
3. Besides the transverse CT slices, the operator can view the SAR distribution over any sagittal or coronal cut (figure 3 and 4).
4. In all views, the tumor is indicated by a white, dashed contour.
5. In the S3DHTP, the input parameters had to be typed in. The Berlin system enters new parameters via interactive graphics on the same display screen.

Besides the above functional improvements, there is one other important change: the Berlin program uses the graphics of the X Window System for the output display. The model generation program and the FDTD program are written in FORTRAN. Therefore, the Berlin program is portable to virtually any workstation.

6 Clinical Application

The Berlin system has been applied in 3 patients which were referred to the Hyperthermia Unit of the Department of Radiooncology. The whole planning procedure proved as clinically well practicable: 15 min for CT scan, 15 min for data transfer, 30–45 min for data compression, contour generation and creation of the patient model, 1 hour per run on the SUN Sparcstation, i.e., for each quadrant and patient position. The time to find a suitable setup from a choice of precalculated frequencies and patient positions and then to specify proper phases and amplitudes turned out to be less than 1 hour. Presently, a try-and-error strategy is conducted by an experienced person with support of simple computational terms such as $\text{SAR}_{\max}(\text{tumor}) / \text{SAR}_{\max}(\text{normal tissue})$.

Fig. 1–4 depict a specified SAR distribution in three planes for such a patient suffering from presacrally located recurrent rectal cancer which is destroying the sacral bone. A standard pattern at 90 MHz with relative power reduction at the top channel and target point selection [0,-2] (corresponding to a phase delay 36° at bottom and 17° at sides) appears to cover regularly the target volume. Indeed, clinical employment of the proposed SAR distribution yields a relative SAR of 3.8 mW/g/100W in the tumor center (measured invasively corresponding to the gradient of temperature-rise method). With this adjustment at total power of 800 W an effective temperature of $\approx 42^\circ$ C has been achieved in the reference point. Target point selection [0,-1] (phase delay 18° at bottom, 9° at sides) results in a slightly reduced relative SAR in the same measurement point (3.4 mW/g/100W) in accordance with the FDTD simulation.

We note that enhancement of relative SAR in a single point of the tumor does not necessarily indicate a superior power deposition pattern. Refined optimization strategies are under research [13]. However, user interface and available options for graphical display, specifically the colorwash representation, are already appropriate to discover advantageous system parameters for heat treatment in reasonable times.

7 Discussion

A patient specific, 3D treatment planning system for deep regional hyperthermia has been developed and put into clinical practice. It represents an improvement to a previous system by presenting better graphics capability, and making portability to other sites much easier.

It is hoped that the portability of this system will lead to the wider use of patient specific 3D treatment planning of deep regional hyperthermia.

Possibly, this will lead to more effective treatments, and make it easier for practitioners in this field to share clinical experience and perhaps establish quantitative figures of merit for this therapy.

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Figure 1: Simulation of the SAR distribution in a patient being treated in the Sigma 60 applicator (frequency: 90 MHz, phase delays: bottom 36° , sides 17° , relative power amplitudes: bottom 1.00, top 0.53, sides 0.76, corresponding to target point selection [0,-2]). Contours are at intervals of 10%, with yellow being the highest and blue the lowest. The red line in the smaller sagittal figure on the right shows which transverse level is being viewed. The tumor is outlined by white dots.

Figure 2: Same as figure 1, but using a colorwash instead of contour lines. Yellow represents highest SAR values and blue the lowest.

Figure 3: Sagittal view. Note that the location of this view is indicated by the red line through the smaller transverse view on the right.

Figure 4: Coronal (frontal) view.