DESIGN OF AN INNOVATIVE WATER FILTER
FOR TOTAL BODY IRRADIATION

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ABSTRACT

Total Body Irradiation (TBI) is a radiological therapy mainly used for patient conditioning before bone marrow transplantation. Basically, the therapy consists in delivering a suited X-ray dose to the entire body of the patient. Achieving a uniform dose over the whole body is one of the major problems because of variations in thickness and density of patient’s tissues. This paper presents the design of an innovative integrated system for improving dose homogeneity in TBI.

The system is made up of a translating bed, an X-ray linear accelerator, a vision system for body thickness assessment, a dynamically controlled water filter and a main control unit for modules integration and synchronization. The core of the system is the water filter, which consists in an array of 70 small water containers (referred to as \textit{cells}). The filter is located between the X-ray source and the patient. The water level in each cell can be on-line modified introducing a small amount of water through an electric on-off valve. This way, water levels can be regulated so as to modify dose distribution in the transversal direction. Moreover, by translating the bed, dose delivery can be modulated even in the longitudinal direction.

KEY WORDS
Total body irradiation, water filter, water level control.

1. INTRODUCTION

Total Body Irradiation is a necessary component in patient conditioning before bone marrow transplantation in the treatment of acute leukaemia and other haematological diseases. There exist different protocols and facilities to perform the TBI therapy. Every TBI protocol involves one or more external X-ray sources to deliver a given amount of radiation to the entire body of the patient \cite{1}. Unlike traditional radiotherapy, which targets a specific area of the body, TBI must encompass the whole body within the radiation field. This is usually obtained by projecting the X-ray beam over a long distance, the patient being placed within the field in a standing or semi-upright position. Unfortunately, during the therapy the patient has to hold an uncomfortable pose for a long time (typically, dose is delivered among 10 or 12 fractions that can last up to 50 minutes each).

The major challenge in performing a TBI therapy consists in delivering a uniform dose to the whole body. In fact, as radiation absorption depends on both tissue thickness and density (i.e. on tissue equivalent thickness), care must be taken in order to ensure that thicker parts of the patient (such as pelvis) receive adequate radiation dose without overdosing thinner parts (such as neck). This is typically achieved by placing some shielding blocks (made up of metallic or plastic media) between the patient and the source \cite{2,3,4,5,6}. However, shielding blocks design and positioning is a long procedure. Moreover, compensation accuracy is not always satisfactory, being hardly affected by patient’s movements during irradiation. As a result, the therapy turns out to be time-consuming, not repeatable and not always effective.

To address these problems, some new techniques have been developed in the last decades. One among them consists in employing a \textit{translating unit} to move the patient under the radio source. In this way, only a part (a sort of transversal slice) of the patient lies within the X-ray field at each time \cite{7}. With this technique, the patient comfortably rests in supine or prone position and is moved slowly below the gantry, that stands in upright position. Correct dose delivery is obtained by modifying the translation velocity, which is calculated by taking into account some physical parameters such as patient’s dimensions and density, beam geometry and machine dose rate. It has been proved that the translating unit technique provides better dose uniformity within the
patient, if compared to fixed beam techniques, and makes shielding blocks placement more accurate [8]. Moreover, translating-bed techniques are comfortable for patient and allow placing the patient closer to the X-ray source [9]. However, these techniques provide dose uniformity only in the translation direction, making the use of a compensator necessary in order to achieve homogeneous dose distribution in the transversal direction. In order to make the compensator suited to fit different patients, in this work we propose the use of water as compensating media, plus a control system to dynamically change the shape of the compensator. Water-based compensating filtering in TBI is a promising technique that has been recently investigated. Shigeo et al. carried out basic studies on a water compensator, to be placed between the patient and a 10MV linear accelerator [10]. By means of phantom tests, they calculated the shape of the water compensator that makes the absorbed dose uniform in the whole body.

Figure 1. Water compensating filter principle.

In this paper, the design of an innovative controlled water filter is presented. The solution proposed here combines translation with a new flexible compensator (figure 1), that is fixed with respect to the radio source and covers the whole radio beam spot. The system is made up of an array of 70 cells. Each cell can be partially filled with water by means of a hydraulic circuit. The great advantage of this device is that water levels can be on-line modified during translation, according to patient’s geometry and position. In this way, different patients can be treated by simply reprogramming the control system, so that the time required for treatment planning and system setup is strongly reduced. It is believed that, by making use of this innovative water filter, TBI therapy could be delivered in a more effective and repeatable way. At the same time, the whole therapy protocol should result much more comfortable from both a psychological and a practical point of view.

Further on, the basic principles of the water filter are introduced (section 2), the water level control scheme is discussed (section 3) and the design of all the modules the system is made of is presented (section 4).

2. WATER FILTER SYSTEM

The water filter system is made up of the following electromechanical modules: a translating unit, the water filter, an X-ray source, two vision systems and a PC-based main control unit (see figure 2). The translating unit moves by means of a brushless electric motor, located under the bed. Translation velocity is kept constant, since longitudinal dose homogeneity can be achieved by changing water levels during translation. Being the gantry located at a large distance from the patient (nearly 2m), X-rays are assumed to be parallel when hitting the patient. The X-ray beam spot has a rectangular shape, so that an approximately 10cm long transversal section of the body can be irradiated at a time.

Figure 2: System overall scheme.

The water filter is located between the patient and the source and is fixed with respect to the source. The filter is made by a sandwich of 70 side-by-side small containers (1cm large, 10cm long) referred to as cells. Each cell is filled with water through an electric on-off filling valve. Moreover, the water continuously flows out of the cell...
through a calibrated orifice. By opportunistly operating the filling valve, it is possible to regulate the water level in each cell (see next section), so as to customize the transversal shape of the water filter according to patient’s geometry and position. Clearly, the water filter can be shaped discontinuously, with a spatial resolution of 1 cm, due to cell width. Nevertheless, it is reasonable to assume that this resolution is suited to compensate the dose properly.

The water level reference values are on-line calculated, according to patient thickness and to pre-acquired patient data such as CT scans. For this reason, a first vision system (referred to as thickness measuring module) has been designed. A camera and a linear laser beam constitute the measuring system. The laser projects a red linear beam with uniform intensity distribution on patient’s body. The TV camera acquires an image that, once properly processed, provides patient transversal thicknesses along the laser projection plane.

A second vision system (referred to as level measuring module) is required to provide the main control unit with the 70 water levels inside the cells. These values are compared to the calculated reference levels, so that a suitable opening time is determined for each filling valve (see next section). The core of the level measuring module is a TV camera which points toward the water filter by means of a 4-mirrors optical system. The optical system has the function of both reducing encumbrance and exploiting the whole camera CCD. In order to facilitate the calculation of the water levels, a small round marker, floating on the water, has been designed.

3. WATER LEVEL CONTROL

In order to regulate the water level inside each cell, a non-linear control system has been developed. The controller compares the desired water level with the measured one and generates the control action, that consists in opening the filling valve for a time which is strictly related to the error. The control unit is made up of two modules: the reference planner module and the water level control module (figure 3). The former module, according to measured body thickness and pre-acquired patient’s data, calculates the desired water level \( h' \) for each cell. In this first stage, this value is set in such a way that the sum of water level and body equivalent thickness along each emission ray is kept constant.

The water level control module, once measured the actual water level \( h'' \), by properly opening the electric filling valve, regulates the water level. Each water cell has its own planner module and its own water level control module.

The control cycle is repeated with a sampling time of \( T=1s \). During this cycle time, water level can change due to two opposite actions:

1) water constantly flows out of the cell through a calibrated orifice (flow \( q_{out} \)), as a consequence, water level goes down;

2) on the contrary, water level can be increased by making external water fill the cell by means of the electric valve (flow \( q_{in} \)).

Clearly, water flows change with water level and can be expressed as follows:

\[
q_{in}(h) = C_{in} A_{in} \sqrt{2g(h_{in} - h)}
\]

\[
q_{out}(h) = C_{out} A_{out} \sqrt{2g(h + h_{out})}
\]

where \( h \) is water level inside the cell, \( h_{in} \) is the inner circuit head, \( h_{out} \) is the outer circuit discharge head, \( C \) and \( A \) are the discharge coefficient and the section of the hydraulic circuits, \( g \) is gravity acceleration.

Every control cycle, the controller opens the valve for a time \( \tau \) that can be up to sampling time \( T \), according to the amount of water needed to compensate for the level error. This way, a Pulse Width Modulation (PWM) controller is implemented.

Let the subscript \( k \) designate time \( t=kT \). The valve opening time for control cycle \( k+1 \) is hence given by the following:

\[
\tau_{k+1} = \frac{A(h_{k+2} - h_{k+1}^{ext}) + Tq_{out}(h_{k+1}^{ext})}{q_{in}(h_{k+1}^{ext})}
\]

where \( A \) is the area of the cell base, while the estimated water level at time \( k+1 \) is yielded by

\[
h_{k+1}^{ext} = h_k^{ext} + \frac{\tau_k q_{in}(h_k^m) - Tq_{out}(h_k^m)}{A}
\]

where the superscript \( m \) stands for measured value and \( \tau_k \) is filling valve opening time for control cycle \( k \) (figure 4).

In other words, the water level controller calculates water levels at time \( k+1 \) in order to get an estimation of both water flows and water level error at time \( k+1 \).

A more complex control scheme is presented in [11], where a state-space controller for a three-cells, four valves system was developed. Nevertheless, for the 70 cells system we decided to control separately each cell.

Figure 3: Water level control scheme.
Moreover, the choice of discharging continuously the cells led us to a simplified mechanic and electronic hardware layout.

![Figure 4: Valve opening time calculation.](image)

In order to tune the water level control module parameters and to choose the best strategy for the reference planner module, a Matlab-based simulation of the system has been carried out. The non-linear dynamic behaviour of the valve and of the cells has been modelled, taking into account hydraulic circuit time delays.

In the following, the technique used by the reference planner to calculate the desired water levels is briefly explained. Water level planning must take into account that a 10cm long portion of the patient is under the cells at a time. This part of the patient has been measured before undergoing the filter by means of the thickness measuring vision system, so this information can be exploited to calculate the reference water levels. In this first stage, some different algorithms have been tested in simulation by simply calculating (and trying to keep constant) the sum of water thickness and patient equivalent thickness, taking into account the fact that each measured transversal section of the patient undergoes the filter for 100 control cycles (translating bed velocity has been set to 1mm/s).

Figure 5 shows simulation results for a control algorithm that calculates the reference water level of each cell as the average of the values required by all patient's sections currently undergoing the cell. Curve number 4 represents the equivalent thickness of patient's section undergoing the laser versus time. Curve number 6 represents the target value for the sum of body thickness and compensating water, while curve number 5 depicts the actual value of that sum, obtained by averaging the water level undergone by a single section on a time base. As it shows, this value tends to be different from target value when patient thickness varies rapidly with time. This phenomenon is evident especially in the neck and in the head. Nevertheless, in our opinion scattering phenomena inside patient’s body should partially compensate for this error. Moreover, initial head overcompensation can be avoided by changing water level at the beginning of simulation.

![Figure 5: Simulation results.](image)

Clearly, water level planning algorithms must be validated on an experimental testbed, by means of phantom dose measurements.

4. MODULES DESIGN

The core of the system is represented by the array of cells. Several solutions have been taken into account and eventually we decided to create a sandwich of U-shaped 1cm thick structures, separated by a 0,2mm thin film. The structures are made out of Plexiglas, while the films are made out of Polyethylene. Both of them are shaped by laser cutting. Films and U structures are glued together and compressed by means of 4 screws that cross all the array of cells. Moreover, at the base of each cell there are two holes, one for the filling pipe, one for continuously draining water. The advantages of this solution are:

- material employed is transparent, so that the vision system can easily detect the position of the floating markers inside the cells;
- the filter is modular in the sense that new cells can be added to the filter just by replacing the 4 screws with longer ones.

In order to test water rig and the effectiveness of the construction steps described above, a small prototype consisting in just 3 cells has been realized (figure 6).

![Figure 6: Water filter prototype.](image)
The hydraulic circuit consists in a set of 70 electric on-off valves connected to the cells and to a cylindrical tank (figure 7). A short flexible corked pipe is connected to one side of the tank in order to absorb the water hammer effect as the valves close. Another tank (upper reservoir), located 1.5m higher than the valves in order to provide a sufficient head, provides the water to the cylindrical tank. Water flowing out from the cells is collected and conveyed to a lower reservoir. The water loop is closed by a submersible pump which moves the water from the lower reservoir to the upper one.

The design of the level measuring module is represented in figure 8. The camera is upright located and points to a V-shaped mirror, which plays the role of splitting in two parts the view field of the TV camera. Thus, by means of two more symmetric mirrors, the top part of the CCD acquires the image of the 35 cells on the left, while the bottom part acquires the remaining 35 cells. In this way, the whole CCD is completely exploited without the need of employing two cameras instead of one.

The system overall layout is shown in figure 9. The chassis on top is intended to hold the water filter (shown), the cylindrical tank, the valves and the vision systems. The translating unit consists in a 15cm high platform provided with 4 non-steering wheels. The platform is moved by means of a brushless motor which operates the shaft of the rear wheels by means of a toothed transmission belt.

The main control unit is currently under development. Basically, we decided to build a power board (figure 10) to control electric valves duty cycle, holding a microcontroller (Microchip PIC16C75B) that manages valves via some MOS latched drivers (Allegro Microsystems UCN5801A). Valve opening times are calculated by a desktop computer holding the TV frame grabbers, and hence transmitted to the microcontroller by means of a parallel interface.

5. CONCLUSION

This work presented the design of an innovative integrated system for improving the level of dose homogeneity in Total Body Irradiation. The use of this system should allow to compensate for tissue heterogeneity in both the longitudinal and the transversal directions. Moreover, the new treatment protocol should result to be less time-consuming, more repeatable and
more easy to plan and setup with respect to traditional protocols.
The paper presented the design of all the modules employed to make the filter effective, together with the control strategy adopted to make the filter shape change during treatment. The implementation of the filter is currently being carried out and we expect to validate the prototype by means of experimental phantom tests.

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