RADIATION-ACOUSTIC MONITORING OF THERAPEUTIC BEAM

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Abstract

A method of dose field control in patient's body during radiation treatment is proposed. It is based on detection of thermoacoustic pulse to be generated by pulsed radiation beam *in vivo* and on reconstruction of dose field characteristics by stress amplitude. A possible scheme of realization of the proposed method is considered. Typical variants of dose fields and corresponding solutions of radiation thermoacoustic equation are discussed. The values of stress pulses and accuracy of dose field location are estimated for electron, X-ray and proton beams.

1 INTRODUCTION

One of lines of advanced medicine is the use of directed beams of ionizing radiation – electrons, X-ray, protons. So, radiosurgery has become an important method of treatment of small lesions such as benign or malignant primary tumors and isolated metastases. For the most effective application of radiation beam without healthy tissue overirradiation one should control characteristics of irradiation zone in the patient's body directly during the treatment, i.e. to determine form, location and dose distribution in this zone. At present, dose field parameters are determined by preliminary calculation that demands thorough initial data preparation, considerable expense of computer time and aware experts in the physics of radiation– matter interaction. This approach does not guarantee coincidence the real dose field with the calculated one because of dispersion of the beam and the target characteristics, personnel's mistakes, etc.

In the paper, a new method of radiation- acoustic monitoring of therapeutic beam is proposed. This method is based on detection of thermoacoustic pulse generated by pulsed radiation beam *in vivo* and recovery on its basis dose field characteristics.

2 METHOD DESCRIPTION

A short-pulsed radiation beam causes "instant" heating of a target material and generation in it a thermoelastic stress pulse which is initially directly proportional to absorbed energy density and diverges from generation zone with longitudinal sound velocity s. Time of pulse arrival to i-th acoustic detector permits determining distance $l_i = t_i s$ from zone of energy release to detector.

The heat energy density $\varepsilon(\vec{r},t)$ to be coincide with absorbed dose determines unambiguously amplitude of generated thermoelastic pulse $\sigma(l,t)$ connected with it by an integral relation of the convolution type. In some particular cases one can express the absorbed dose $\varepsilon(\vec{r},t)$ per thermoelastic pulse amplitude $\sigma(l,t)$ and distance l [1,2]. Indications of several wideband acoustic detectors connected to patient's body permit determining position, form and value of dose field.

A possible scheme of radiation- acoustic monitoring of therapeutic beam in patient's body is shown in Fig. 1. (The case of intracranial irradiation).

Cylinder or converging therapeutic beam (1) goes out a pulsed accelerator (2) passes through filter- transformer (3) of beam characteristics. Thermoacoustic dosimeters of external monitoring (4-6) are positioned on the path of the beam. Passing through the dosimeter the beam generates the thermoacoustic pulse containing information concerning particle distribution, duration and diameter of the beam. Joint data at least of two dosimeters permit determining axis direction and angle of convergence of the beam. Coming in detectors (7-9) the acoustic pulses transform into the voltage ones which go to **SYGNAL PROCESSING SYSTEM (SPS)**. Also, accelerator sync pulse and signals from internal monitoring detectors (10-13) detecting thermoacoustic pulse from dose field in patient's body come there with corresponding delays. **SPS** determines position, form and value of dose field. The number of detectors is chosen assuming necessary accuracy of measurements. Dose field data come in **CONTROLLED COMPUTER** that yields directive on change of relative position of radiation source and target.

3 THEORETICAL JUSTIFICATION

3.1 Radiation-Acoustic Equation and Solutions

The thermoacoustic displacement potential $\Psi(\vec{r},t)$ is found from the wave equation [2]:

$$\frac{\partial^2\Psi(\vec{r},t)}{\partial t^2} - s^2\Delta\Psi(\vec{r},t) = -\frac{\Gamma}{\rho}\varepsilon(\vec{r},t)\,, \qquad \mathbf{(1)}$$

Here Γ and ρ are the Gruneisen's parameter and density.

The solution of Eq. (1) for unbounded medium is:

$$\Psi(\vec{r}_0,t) = -\frac{\Gamma}{4\pi\rho s^2}\iiint \frac{\varepsilon\left(\vec{r},t-\dfrac{|\vec{r}_0-\vec{r}|}{s}\right)}{|\vec{r}_0-\vec{r}|}\,dxdydz \quad , \qquad \mathbf{(2)}$$

where $\vec{r}_0$ is the position vector of the observation point. The range of integration is $|\vec{r}_0-\vec{r}| \le st$. For quasi-liquid medium, we have the following expression for nonzero (diagonal) elements of the stress tensor:

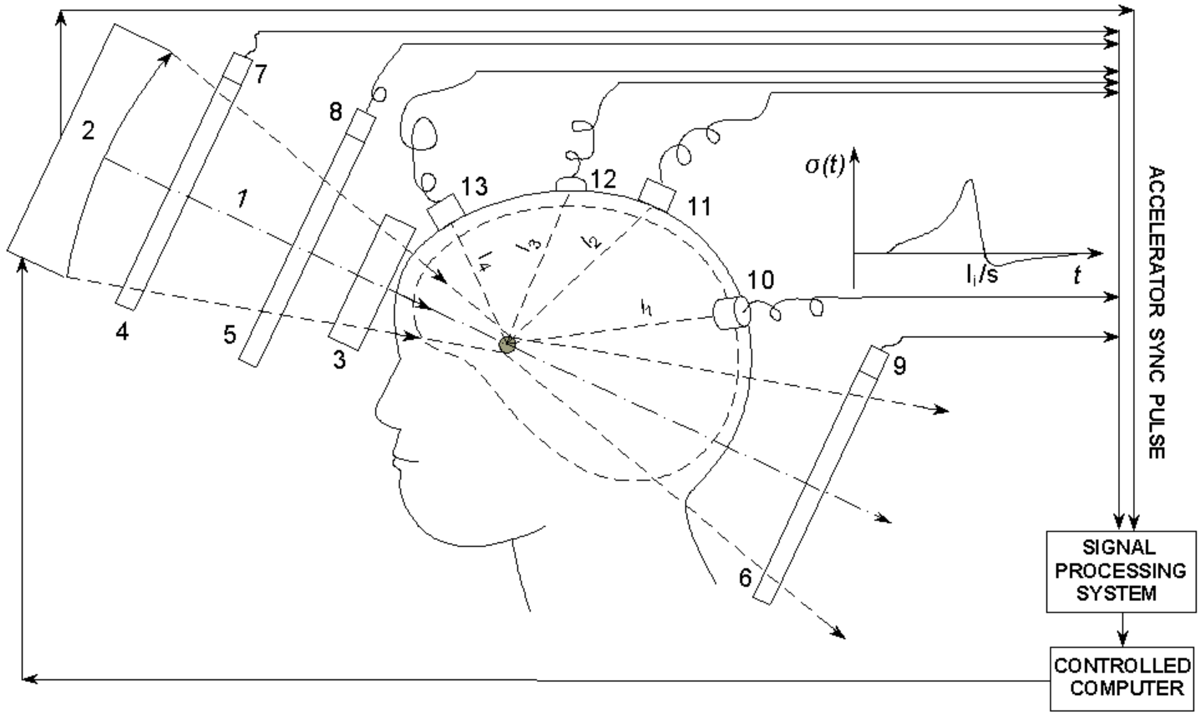

Figure 1: Scheme of radiation- acoustic monitoring of therapeutic beam in patient's body-

$$\sigma(\vec{r}_0,t)=\rho\frac{\partial^2\Psi}{\partial t^2}+\Gamma\varepsilon=$$

$$=-\frac{\Gamma}{4\pi s^2}\frac{\partial^2}{\partial t^2}\iiint\frac{\varepsilon\left(\vec{r},t-\frac{|\vec{r}_0-\vec{r}|}{s}\right)}{|\vec{r}_0-\vec{r}|}dxdydz\text{ , }(r_0>>D/2).\quad \textbf{(3)}$$

For some special dose fields, Eq. (3) permits a simpler analytical representation. It simplifies reconstruction of the dose field $\varepsilon(\vec{r},t)$ by thermoacoustic response of the target. The simplest pulse form produces one-dimensional instant radiation heating of the target material: $\varepsilon(\vec{r},t)\equiv\varepsilon(x)\theta(t)$. In this case the thermoacoustic pulse propagating in positive direction of x-axis has the form

$$\sigma(x,t)=\frac{\Gamma}{2}\varepsilon(x-st),\quad \textbf{(4)}$$

i.e. the acoustic response $\sigma(x,t)$ is directly proportional to dose field $\varepsilon(x-st)$ in the target, and its time delay determines distance from generation zone to observation point. In case of near-surface irradiation the total pulse consists of superposition of direct and reflected pulses.

The thermoacoustic responses of cylinder or spherical dose fields have more complex forms. The corresponding expressions for stress amplitudes as well as the inverse problem solutions were found and analyzed in [1,2].

3.2 Dose Field Characterization

Therapeutic beam characteristics, i.e. sort and energy of its particles, diameter D, duration T, are chosen depending on location and form of irradiated lesion. These characteristics determine a type of a dose field behaving as the thermal loading in the thermoacoustic equation. Consider some specific features of dose fields generating by electron and X-ray and proton beams.

A small dose spot formation on considerable depth of tissue by pencil or focused electron beam is problematic. Electron beam can be used for surface and near-surface irradiation. Existing program packages permit finding the dose field of arbitrary electron beam [3]. These codes allow justifying results of radiation-acoustic dosimetry. In the case of $X<<D$, and flat surface of the target, the quasi-one-dimensional acoustic response (4) is realized. Here X is the maximum penetration depth.

A pencil beam of monoenergetic photons attenuates in matter exponentially. Supposing axisymmetric Gaussian distribution of photons with initial radius R we have the following expression for dose field of a pulsed converging photon beam in (semi)infinite medium:

$$\varepsilon_\gamma(x,r,t)=\frac{N_\gamma E_\gamma \mu_{en}(E_\gamma)\varphi(t)\,e^{-\mu(E_\gamma)x-\frac{r^2}{R^2\left(1-\frac{x}{f}\right)^2+\Delta r^2}}}{\pi\left[R^2\left(1-\frac{x}{f}\right)^2+\Delta r^2\right]}\text{ , }\textbf{(5)}$$

where N_γ is the total number of photons, $\mu(E_\gamma)$ and $\mu_{en}(E_\gamma)$ are the extinction coefficient and the energy absorption coefficient depending on gamma quantum energy E_γ, f is the focal distance and Δr is the focal spot radius. The function $\varphi(t)$ determines the time dependence of absorbed dose. The following one-parameter approximation $\varphi(t)=0.5(1+\mathrm{erf}(2t/T))$ is mostly acceptable for electron and proton beams. The instant heating approximation $\varphi(t)=\theta(t)$ is realized under condition $T << R/s$. Here $\theta(t)$ is the Heavyside's unitary function. In this case the dose field recovery is possible by indications of a few detectors.

The extreme case $f \to \infty$ corresponds to a pencil (nonconvergent) beam. Besides, if the condition $\mu(E_\gamma)x << 1$ is satisfied everywhere in the target then the dose field depends on the only spatial variable r. In this case the solving of the inverse problem is facilitated and one can reconstruct the dose field $\varepsilon(r)$ by indications of the only detector [1,2].

For ionization loss of nonrelativistic proton with energy E from 10 MeV to 200 MeV, one can use the approximate expression $dE/dx \approx -B/E$ where $B \approx 2 \cdot 10^3 \rho$, MeV^{2}cm^{2}g^{-1}. Within the framework of this approximation, the expression for the dose field of a focused proton beam is

$$\varepsilon_p(x,r,t) = \frac{NB\theta(E^2 - 2Bx)}{\sqrt{E^2 - 2B(x - \Delta x)}} \frac{\varphi(t)\, e^{-\frac{r^2}{R^2\left(1-\frac{x}{f}\right)^2 + \Delta r^2}}}{\pi\left[R^2\left(1-\frac{x}{f}\right)^2 + \Delta r^2\right]}, \quad \textbf{(6)}$$

where N is the number of protons in the beam pulse, $\Delta x \approx 1.3$ cm is the fitting parameter of the model. Limit $f \to \infty$ corresponds to the case of the pencil beam.

Brought dose field characteristics are the initial information for simulating thermoacoustic response of a target. This simulation helps solve the basic problem: to reconstruct *in vivo* or in phantom position, form and value of dose field by thermoacoustic response of the target.

3.3 Numerical Estimations

Consider the thermoacoustic responses of biological tissue on pulsed electron, X-ray and proton irradiation.

The estimation of absorbed dose of relativistic electron beam is $\varepsilon_e \approx \frac{N_e}{\pi R^2}\chi_{ion}\rho$, where $\chi_{ion} \approx 2$ MeV·cm^2/g is the linear energy loss of relativistic electron , N_e – is the number of electrons in the pulse. Assuming $N_e = 10^{10}$, $R = 1$ cm, $\rho = 1$ g/cm^3, we have $\varepsilon_e = 1$ Gy. The stress pulse value σ in case of one-dimensional dose field can be estimated by (4). Assuming $\Gamma = 0.2$ we have $\sigma \approx 100$ Pa.

For bremsstrahlung beam generating by electron beam, the estimation of absorbed dose is the following $\varepsilon_\gamma \approx \frac{k_{e\gamma}E_e N_e \mu_{en}}{\pi R^2}$. Here $k_{e\gamma}$ is the conversion coefficient of electron to gamma energy. Assuming $E_e = 8$ MeV, $E_\gamma = 0.4$ MeV, $k_{e\gamma} = 0.1$ [4], $N_e = 10^{10}$, $\mu_{en} \approx 0.03$ cm^{-1}, $R = 1$ cm we have $\varepsilon_\gamma \approx 0.03$ Gy. One can estimate the stress pulse value from instant cylinder photon beam by equation $\sigma(l) \approx 0.32 \cdot \Gamma\varepsilon(R/l)^{1/2}\left(1 + s^2T^2/4R^2\right)^{-3/4}$. Assuming $T = 0$, $\Gamma = 0.2$, $R = 0.5$ cm, $l = 5$ cm we have $\sigma \approx 0.5$ Pa that is approximately in ten times exceeds threshold of sensitivity of wideband acoustic detector with passband from 0 to 0.5 MHz at room temperature [2]. The use of high-intensive and focused electron beams permits obtaining X-ray beams that in 100 to 1000 times exceed the above. On the other hand, they are not harmful because produce dose $\varepsilon \le 1$ Gy to be small compared with really used therapeutic doses.

The proton energy loss increases considerably at the end of its range (so-called the Bragg's peak). The absorbed dose estimation by (6) in the Bragg's peak for the proton beam with $N = 10^{10}$ and $R = 1$ cm results the value $\varepsilon_p \approx 20$ Gy. Given the focusing and the Bragg's peak effect the absorbed dose in focus can exceed considerably the external one. So one can use expression $\sigma(l) \approx 0.21 \cdot \Gamma\varepsilon(R/l)\left(1 + s^2T^2/4R^2\right)^{-1}$ to be valid in the wave zone of the spherically symmetric Gaussian dose field. Assuming $T = 0$, $\Gamma = 0.2$, $R = 0.5$ cm, $l = 5$ cm we have $\sigma \approx 80$ Pa

The accuracy of positioning of flat, cylinder and spherical dose fields is approximately equal to $\Delta r \approx \sqrt{R^2 + (sT/2)^2}$ if one can neglect sound absorption and dispersion.

4 CONCLUSION

On the basis of authors' experience in thermoacoustic dosimetry of unmoved and scanning pulsed radiation beams [1,2], the method and possible scheme of radiation-acoustic monitoring of therapeutic beam in patient's body was considered.

Parallel indications of several wideband acoustic detectors connected to patient's body or to phantom permit determining position, form and value of dose field during irradiation. The estimations have shown that really used therapeutic doses are much more then those necessary for reliable thermoacoustic dosimetry. It validates realizability and safety of the proposed method. Sound absorption and dispersion as long irradiation time and presence of reflected pulse impair the accuracy of determination of above characteristics.

5 REFERENCES

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