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Modeling radiation doses to critical organs of patients undergoing intracavitary brachytherapy treatment using the finite element method

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ABSTRACT

Intracavitary brachytherapy is a procedure in which radioactive sources are placed in the body cavities close to or inside the target volume to deliver radiation at short distances. In this mode of treatment, high radiation dose can be delivered to the tumour volume with rapid dose fall-off into the surrounding normal tissues. In brachytherapy, the dosimetry in biological tissues is a complex process. Dosimetric parameters such as the dose to critical organs and the total dose to the reference points as in the case of Manchester system are critical for patients undergoing intracavitary brachytherapy treatment. In this study, the finite element method has been utilized to solve Boltzmann Transport Equation (BTE) to determine the distribution of angular photon fluxes at various positions in the cervix of cancer patients and the dose distribution calculated for the organs of interest. Results from the study indicate doses to the rectum and the bladder to be in the range of 21.5-90.10cGy and 25.60-110.02cGy respectively for stage I to stage IV cancer patients. Comparison of the results from this model with data from published articles and dose prescriptions from the treatment planning system of the Radiotherapy Centre of the Komfo Anokye Teaching Hospital in Ghana for different cancer stages indicate good agreement.

Introduction

Brachytherapy is the short distance treatment procedures of malignant diseases or tumors with radioactive sources coming from encapsulated sources. The radioactive sources are placed either directly into the tumor or near the tumor to deliver radiations at short distances[1]. The purpose of brachytherapy treatment is to destroy the cancer cells with ionizing radiation by localizing high radiation dose in the tumor volume while the normal tissues and critical organs receive as low dose as possible[2,3]. Brachytherapy is important for the achievement of local disease control in cervical cancer. In this mode of treatment, high radiation dose can be delivered to the target volume with rapid dose fall-off in the surrounding normaltissues[4,5].

In this study, radiation doses to critical organs has been modelled using the Finite Element Method(FEM) to solve the photon transport equation in heterogeneous media[6-8]. The photon transport in tissues is restricted to geometries that are cylindrically symmetric around the incident photon. The use of the FEM as a mathematical tool to solve the PTE in anintegro-differential formwill therefore be a confirmatory determination of radiation doses to the critical organs and tumorvolume[9,10]. The FEM is very fast, accurate and therefore the results obtained will enhance the speed and accuracy of the treatment planning system for patients undergoing intracavitary brachytherapy treatment.

Method of Analysis

This model is based on the solution of the Boltzmann transport equation using the finite element method. The mathematical formulation of photon transport equation is written as

$$\frac{1}{c}\frac{\partial\Phi(r,\Omega,t)}{\partial t} = S(r,\Omega,t) - \Omega\nabla\Phi(r,\Omega,t) - \mu_t\Phi(r,\Omega,t) + \mu_s\int_0^{2\pi} f(\Omega,\Omega')\Phi(r,\Omega',t)\partial\Omega' \quad (1)$$

where r is the position vector, c is the velocity of light and Ω is the unit vector in the direction of photon propagation. $\Phi(r,\Omega,t)$ is the photon flux. $S(r,\Omega,t)$ is the source term and represents the photon activity injected into a solid angle centred on Ω in a unit volume at r. The phase function $f(\Omega,\Omega')$ describing the probability that during any scattering event, a photon with direction Ω' is scattered into the direction Ω and $\mu_t = \mu_t + \mu_s$ is the total attenuation co-efficient in tissue.

After discretization and solving for Φ in equation(1); the following system of matrix equations are obtained

$$\frac{1}{c}P\dot{\Phi}(t) + A\Phi(t) = S(t) \quad (2)$$

where P and A are system of matrix coefficients, the fluxes are $\dot{\Phi}$, Φ and S is the source term. The fluxes and the source term are defined as:

Also the subscripts in equation (3) denotes the various tumourstages with the corresponding source terms (S).

The absorbed dose distribution is computed from the particle fluxes obtained fromequation(2). The absorbed dose by the tissue is therefore calculated using the equation (4) as follows

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$$\dot{\Phi} = \begin{pmatrix} \dot{\Phi}_1(t) \\ \dot{\Phi}_2(t) \\ . \\ . \\ . \\ \dot{\Phi}_N(t) \end{pmatrix}; \quad \Phi = \begin{pmatrix} \Phi_1(t) \\ \Phi_2(t) \\ . \\ . \\ . \\ \Phi_N(t) \end{pmatrix} \text{and} \quad S = \begin{pmatrix} S_1(t) \\ S_2(t) \\ . \\ . \\ . \\ S_N(t) \end{pmatrix} \tag{3}$$

$$D(r,E) = \int_r \int_E \Phi(r,E) \frac{\mu_{en}}{\rho}(E) \partial E \partial r \tag{4}$$

where $\frac{\mu_{en}}{\rho}(E)$ is the mass-energy absorption coefficient of the material or medium. The discretized form of equation(4) is

$$D(r_i, E_j) = \sum_i^r \sum_j^N \Phi(r_i, E_j) \frac{\mu_{en}}{\rho}(E_j) \tag{5}$$

Results and Discussions

Figure.1 shows the source term characteristics as a function of distance. The source was assumed to be Cs-137 spherical pellets arranged in line geometry. The source strength for the various treatment regimes corresponding to different cancer stages was determined. In the treatment of cervical cancer in brachytherapy, the same source with a specific source strength is used. The different stages of the cancer are treated by exposing the cancerous tissues to different time regimes resulting in specific photon fluxes. The photon fluxes result in specific dose distributions depending on whether the treatment is delivered over a short time for a single large dose or over prolonged periods of time corresponding to fractionated doses. Figure 1 it shows that, the source strength increases to a maximum at about 1cm and then decreasing again to zero for the next 5cm.

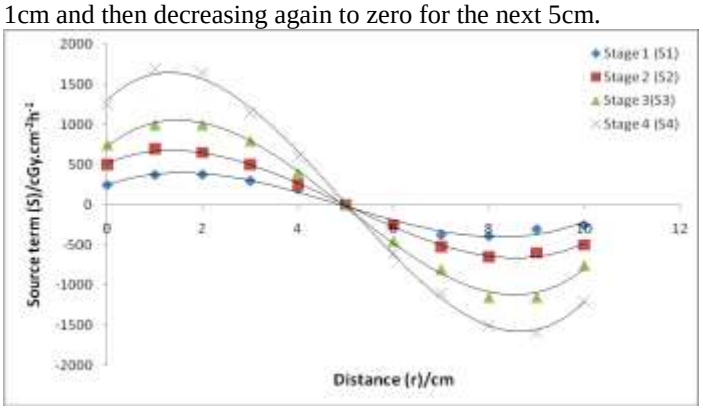

Fig 1. Source strength distribution as a function of distance

The photon flux distribution as a function of distance is shown in Figure 2. The Figure 2,indicates increase in the photon fluxes over a distance of 5cm and then decreases for the rest of the distance. A similar trend is observed in Figure 3 for the corresponding doses. This observation is attributed to the interaction of the photon fluxes with the tissues, which initially results in an increase (build-up) until they reach the peak, but slowly decreases when there is more scattering, anisotropy and attenuation effect.

Dose Profile Analysis

The dose distribution is shown in Figure 3. The distribution is characterized by an increase to a distance of 5cm followed by a decrease for the rest of the distance as it approaches the boundaries. The figure represents the corresponding dose due to the photon flux and therefore has similar characteristics as that of Figure 2.

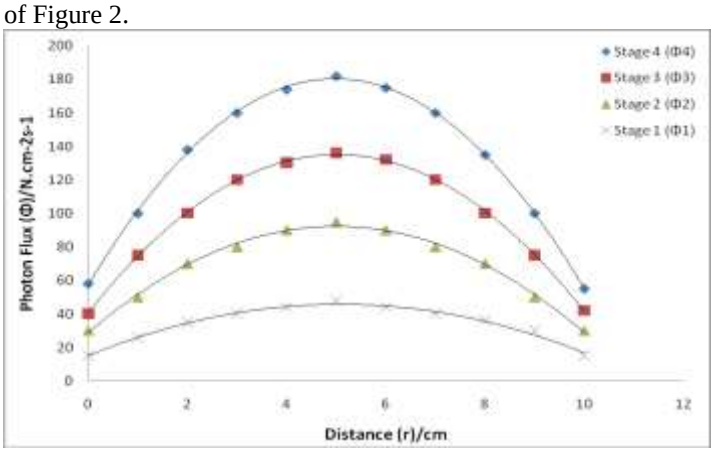

Fig 2: Photon flux distribution for different cancer stages as a function of distance

The graph gives a general overview of the relationship between the dose prescriptions for the different treatment regimes corresponding to the different stages of cancer. It also indicates that, the greater the photon flux the higher the corresponding dose delivered to the tumour. The target volumes and the critical organs like the rectum and bladder, have specific distances from the source point depending on the patient's anatomical structure. The thicknesses of the rectum and the bladder, the specific distances between the source point and the target volumes depend on the patient's size and weight.

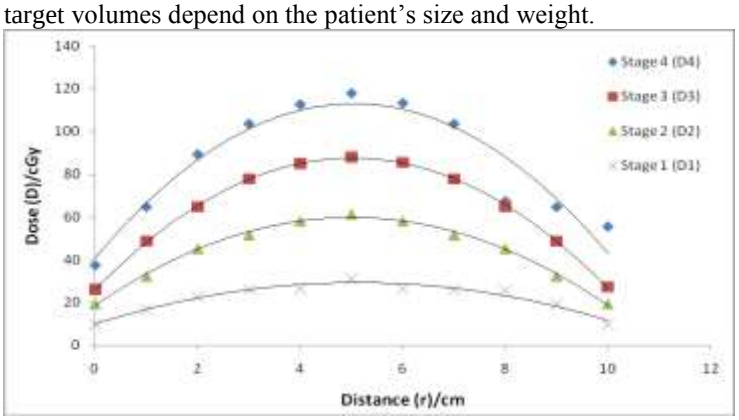

Fig 3: Variation of dose as a function of distance for different cancer stages

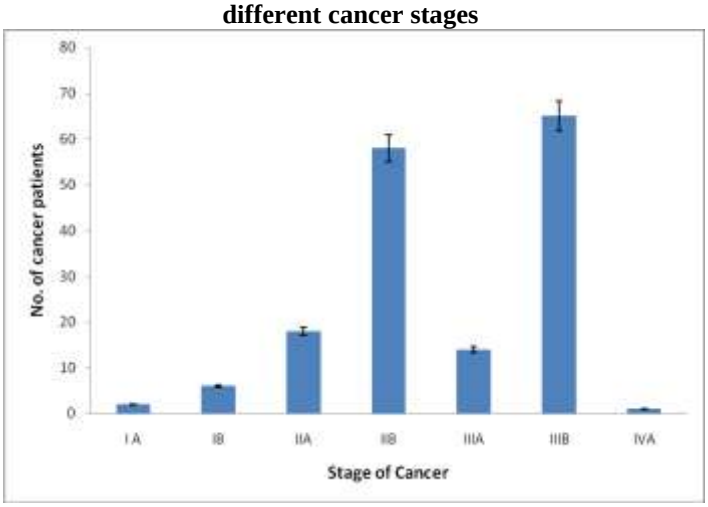

Fig 4. Variation of the number of cancerpatients with cancer stages

Figure 4 shows the various tumor stages with the corresponding group of patients. The total number of patients was about 164 collated for the analysis. From the analysis, it is shown that the highest number observed was found to be about

65 patients corresponding to stage IIIB and the least was only 1 (one) patient representing stage IVA. These two stages accounts for advance tumor stages.

Comparison with Published Data and Treatment Planning System of KomfoAnokye Teaching Hospital

Comparison of the average rectum and bladder doses from this study and Monte Carlo values(Miguel et al 2002) are shown in Table 1. In general, the rectal and bladder doses from Monte Carlo are within the values obtained from this study.

The results from the study were also compared with published data using TLD and treatment planning system(TPS) of the KomfoAnokye Teaching Hospital (KATH). The results show variations between the method and published articles and the KATH Treatment Planning System. Data from the KATH treatment planning system covered one hundred and sixty –four patients who were referred to the hospital for treatment.

Table 1. Comparison of this model with Published data

Method	Rectum (cGy)	Bladder (cGy)	Reference
TLD	22.13 - 63.76	-	[11]
TLD	-	18.99 - 46.36	[12]
TPS	10.13 – 85.67	21.32 – 78.81	[13]
Monte Carlo simulations	78.71±0.36	29.04±0.24	[14]
FEM	21.5 - 90.10	25.60 – 110.02	This model

Conclusion

To date, a number of theoretical and experimental methods have been applied in the treatment planning systems at various Oncology Centres. These include the AAPM (TG-43), Monte Carlo simulations and Sievert Intregral method. The method used in this study is based on the application of the finite element method (FEM) in the solution of the Boltzmann's transport equation in biological tissues. Doses to the rectum and the bladder were determined by simulation using MATLAB and Microsoft Excel. The results show doses to the rectum and bladder to be in the range of 10.13-85.67cGy and 21.32-78.81cGy respectively for stage I to stage IV patients. This agrees well with the data generated by the Treatment Planning System at the Oncology Centre of KomfoAnokye Teaching Hospital in Ghana.

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