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DOSE DISTRIBUTION, INTEGRAL DOSE AND RADIATION RISK IN COMPUTERIZED TOMOGRAPHY OF THE SKULL

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The dose distribution and the integral dose for CT-examinations of the skull can be obtained experimentally from a three-dimensional array of TL-dosimeters in a tissue-equivalent phantom. In this paper we propose a new method which is based on two measured dose profiles for a single scan: f(z) along the central body axis z, and f(x,y) in the x-y plane perpendicular to z and parallel to the single phantom slices. Both dose profiles were measured with Harshaw TLD 100 rods and ribbons in an Alderson phantom in supine position. The computer - aided superposition of both dose profiles allows us then to reconstruct the spatial dose distribution and to compute the integral dose for any combination of scans. The application of this method is illustrated for a standard brain examination consisting of 14 scans adjacent to each other with a FWHM of the beam profile of 9 mm. The validity of this procedure was checked by comparing the theoretical reconstruction with TL-measurements revealing excellent agreement between calculation and experiment.

Introduction

Radiation dose D, i.e. energy absorbed per unit mass, is commonly accepted as the primary physical quantity of a radiation field which is most appropriate for a correlation with observed biological effects. The significance of the number of cells at risk to biological response, frequently observed in experimental and chemical studies, however, gave rise to an alternative concept, the "integral dose", defined as the total energy imparted [1,2] This quantity has been used to estimate the risk of inducing a malignant disease by the highly nonuniform partial body X-irradiation as performed in diagnostic radiological examinations [3].

The integral dose for CT-examinations of the skull can be derived either from a simple measurement of the forehead surface dose [4] or from a three-dimensional array of TL-dosimeters in a tissue - equivalent phantom [5]. In this paper we propose a new method, based on a computer-aided superposition of two dose profiles, measured for a single scan, which allows the computation of the integral dose for any combination of scans.

Absorbed dose vs. integral dose

One of the basic assumptions in carcinogenesis is that the transformation and emergence of a single cell will lead to an observable tumour. Since the chance of emergence of a transformed cell from a uniformly irradiated mass of similar cells is proportional to the number of cells at

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risk, it follows that the chance of a malignant disease for a given dose would be proportional to the mass of the organism. It is certainly not true that large animals develop neoplasms with a much higher incidence than smaller ones [2]. However, there is much experimental evidence that as we increase the fraction of a tissue or organ irradiated to a given dose level, the biological effect increases, a fact which led to the introduction of the integral dose in 1940 [1]. Particularly for a very nonuniform dose distribution, the dose at a given point or the maximum dose anywhere in the organism alone are inadequate criteria for the general toxic effect. Chromosome abnormalities [2] or the induction of animal tumours, e.g. radiation-induced mammary gland neoplasia in the rat [6] clearly support the significance of the number of cells at risk. Although we are far from any certainty, the most probable guess seems to be that the fraction of cells irradiated, or the ratio of transformed to normal cells is a very important quantity in radiobiology. This may also depend on the dose level, for at very low doses a large number of cells must be at risk to give the specified chance of malignancy, while for large doses the necessary number of cells at risk to give the same effect is correspondingly small.

TL-measurements of the dose profiles

Our new method of the calculation of the spatial dose distribution and the resulting integral dose for any number of scans is based on the computer-aided superposition of two measured dose profiles for a single scan parallel to the phantom slices: $f(z)$ along the central body axis z, and $f(x,y)$ in the x-y plane perpendicular to z. Both dose profiles were measured with Harshaw TLD 100 rods and ribbons in an Alderson phantom irradiated in supine position by a Tomoscan 310. TL-measurements were performed for the two standard beam profiles of 3 mm and 9 mm FWHM.

$f(z)$-distributions show a pronounced maximum in the center of the dose profile (16 ± 2mGy for 3 mm, and 18 ± 2 mGy for 9 mm), a width equivalent to the selected FWHM of the beam, and a small dose contribution due to scattering up to approximately 80 mm off the center. In the x-y plane a rather uniform dose distribution could be observed, displaying a linear decrease from the outer bone section to the center of the plane (soft tissue) of only approximately 10 %. Dose profiles $f(z)$ and $f(x,y)$ show only minor variations in different phantom slices of the head, suggesting that both measured dose profiles can be used for any location along the central body axis in the head (the only exception being the outer parts because of anatomical differences).

Dose calculations

For the calculation of the dose distribution and the integral dose we assume that (1) $f(z)$ is symmetric around the center of the profile, (2) $f(z)$

and $f(x,y)$ are the same for any location along the z-axis, and (3) for any angle of incidence (angle between the fixed central body axis z and the axis z' normal to the beam) $f(z') = f(z)$. The latter assumption is necessary for the calculation of the integral dose, for the percentage of soft tissue and bone, resp. is only known for the single phantom slices, thus requiring an incidence normal to the z-axis. Each phantom slice of 25 mm thickness is then divided into 25 parallel layers. For a single scan, the dose D_i in a given point $P_i(x_i,y_i,z_i)$ is given by the product of $f(z_i)$ times $f(x_i,y_i)$. For the calculation of dose D_i for any combination of scans, the dose contributions from the different scans have to be summed up, considering their respective position along the z-axis.

Averaging over all points in a given layer and over all layers of a given phantom slice yields the mean dose $\bar{D}_n$ in phantom slice n. Multiplication of D_i by the mass of a 1 mm^3 tissue volume and summation over all mass elements of slice n, weighted by the percentage of bone and soft tissue in this slice, gives then the corresponding integral dose E_n the sum of which is the integral dose E for a given CT-examination.

For a standard examination of the brain, consisting of 14 scans adjacent to each other with a beam of 9 mm FWHM, the results for $\bar{D}_n$ and E_n are presented in columns 1 and 2 of Tab. I.

TABLE I

Mean absorbed dose and integral dose for a standard CT-examination consisting of 14 scans adjacent to each other with a FWHM of the beam profile of 9mm

Phantom slice n	Mean absorbed dose $\bar{D}_n$ [mGy]	Integral dose E_n [mJ] derived from f(z) and f(x,y)	Integral dose E_n [mJ] derived from TL-measurements
0	34.6	16.9	20.1
1	45.4	30.0	30.8
2	48.4	35.9	34.4
3	47.0	33.1	33.3
4	40.1	24.3	25.5
5	17.1	8.8	8.6
6	4.8	2.4	1.6
7	1.0	0.4	0.7
		151.8	155.0

In order to check the validity of our method, we measured the dose in numerous points of the head and calculated the integral dose according to the procedure suggested by Schmidt et al [5] (column 3 of Tab. 1). The surprisingly good agreement demonstrates the applicability of our method, at least compared to other already established methods. The main virtue of our method is that, if once f(z) and f(x,y) are measured, the dose in any given point and the integral dose can be calculated for any combination of scans, without having to perform measurements for each single case.

Risk estimate

The cumulative probability, p, for the development of a radiation-induced malignant neoplasm can be obtained by multiplying the integral dose E with the mean integral incidence function, G_t [3]. For this incidence function which reflects the inducibility of organs and tissues in trunk and head we assume a value of 0.27 kJ^{-1}, derived by Pauly [3] from mortality risk factors. Thus using the above calculated integral dose of 152 mJ, this CT-examination of the skull leads to an induction probability of 4.1×10^{-5} for the head, assuming the same inducibility for head and trunk. This risk is approximately two orders of magnitude smaller than the risk of dying from a spontaneous tumour of the brain [3].

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