PhD Thesis title: 'The sensitivity of radiotherapy to tissue composition and its estimation using novel dual energy CT methods'

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ABSTRACT:

Dose distributions from brachytherapy procedures employing low energy photon sources (<50 keV) are significantly modulated by the composition of human tissues due to the photoelectric effect. This fact was well known at the onset of this thesis and motivated an investigation on methods to better assess the composition of tissues. During this thesis the AAPM Task Group 186 published its report recommending the use of model based dose calculation methods (such as the Monte Carlo simulations heavily used in this thesis) capable of accounting for variations of tissue composition to determine brachytherapy dose distributions, supporting the ideas presented in this thesis. Some of the work of this thesis was cited and included in the report.

This thesis explored two main research lines: the use of Monte Carlo methods in brachytherapy dose calculations to assess their sensitivity with respect to tissue composition variations and the role of dual energy CT (DECT) in the estimation of three dimensional low energy photon cross section maps of patients by identifying tissue types.

A general introduction explaining the need to account for tissue heterogeneities is presented in **Chapter 1** along with the objectives of this thesis and an outline of it. The use of Monte Carlo methods in brachytherapy is reviewed in **Chapter 2**. In that chapter it is shown how the use of Monte Carlo methods evolved in the field of brachytherapy, starting from the calculation of dose distributions around a single brachytherapy source to advanced dose calculation platforms designed for dose calculation of brachytherapy treatments. **Chapter 3** makes use of tabulated tissue composition to assess the impact of population variations in composition on brachytherapy dose distributions using low energy sources. For several tissues it is possible to find in the literature average tissue composition as well as compositions considered ± one standard deviation away from the mean. Dose distributions in uniform tissues were calculated to evaluate the impact of these composition variations. Effects ranging from 4% to 30% were observed indicating that using mean tissue compositions may not be sufficiently accurate.

In **Chapter 4** a similar dataset was used to investigate the difference between scoring dose from photons transported in human tissue and depositing their energy in either that tissue or in a reference material which has historically been water. Both quantities can be reported by model based dose calculation algorithms.

Because of the behavior of mass energy absorption coefficients these two quantities are very different (up to 30%) for low energy photons. In the chapter it is shown that the conversion from one quantity to the other does not vary significantly with distance from a given source. This fact simplifies the conversion from one quantity to the other.

DECT is first introduced in **Chapter 5** where it is used to extract the effective atomic number Z_{eff} and relative electron density ρ_{e} of tissues from CT images taken at low and high kVp. In that chapter a SECT-based method of tissue assignment is compared to a method based on DECT using a Z_{eff} and ρ_{e} lookup table. Dose calculations using low energy sources are used as the metric to assess whether tissue assignment is successful. DECT was found to be superior to SECT, although adding noise on the CT images used for DECT analysis decreased the accuracy benefits. This is mostly due to the high noise levels found in Z_{eff} images which are proportional to the ratio of CT images.

In **Chapter 6** measurements taken at a clinical, dual source DECT scanner are compared to ImaSim simulations. That chapter serves as a validation of the methods presented in **Chapter 5**. A calibration phantom was thus scanned at the DECT scanner and simulated in ImaSim where models of the CT scanner spectra and detector response were employed. These models were validated by half value measurements at the scanner. Agreement within 5% was obtained between ImaSim and measurements, validating the methods of **Chapter 5**.

The next two chapters are dedicated to improving the DECT method to resolve some of the issues observed in chapters 5 and 6, namely the underestimation of Z_{eff} for dense materials and the high noise levels on Z_{eff} images. **Chapter 7** presents a method for estimating Z_{eff} from a pair of high and low kVp CT images based on a calibration procedure using a ρ_{e} calibration phantom frequently used in radiation therapy quality assurance. A parameterization of the ratio of high and low attenuation coefficients vs. Z_{eff} is used to fit the measured data. The fit parameters can subsequently be used to convert any measurement to Z_{eff}. The method is simpler than the method employed in chapters 5 and 6 and provides more accurate values for dense materials.

Chapter 8 presents the results of the evaluation of a commercial iterative image reconstruction method. Phantom scans were used to assess the noise reduction afforded by the algorithm. It was found that for a given imaging dose level the reconstruction method could reduce the standard deviation of Z_{eff} by a factor two. Combining this method with an increase of imaging dose (which may be justifiable in the case of radiotherapy patients who will receive a much higher curative dose) can bring Z_{eff} noise levels to an acceptable level of around 0.2 units of Z_{eff}.

The focus on dose distributions is relaxed in **Chapter 9** where an attempt was made to estimate concentrations of carbon and oxygen in human tissues using DECT methods. Using the lookup table technique of **Chapter 5** DECT-derived Z_{eff} and ρ_{e} are converted into a tissue type whose composition is used to assign concentrations of C and O. The method was found to be superior to the state of the art SECT-based stoichiometric calibration procedure.

Finally **Chapter 10** gives a general discussion of the use of DECT in brachytherapy and proposes methods for clinical implementation. Besides the lookup table approach of Chapter 5 a MC tissue substitute method based on Z_{eff} is also suggested. Future perspectives in the field of particle therapy, namely estimation of stopping power ratio for dose calculation, are also discussed.

References to author publications that relate specifically to the dissertation:

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