Monte Carlo modelling of the patient and treatment delivery complexities for high dose rate branchytherapy

VALORIZATION ADDENDUM

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Brachytherapy has been under continuous development for more than a century now, improved outcomes result from increased accuracy in radiation delivery. Currently, the conventional water based dose formalism, TG-43U1, is being replaced with more accurate models. However, important technical challenges need to be overcome before a definitive clinical implementation of the recently developed technologies can be realised. Some of these aspects were evaluated in this thesis, aiming to provide knowledge and resources to move towards more accurate treatment plans and radiation dose delivery.

This study was performed in two countries, Brazil and the Netherlands, in collaboration with hospitals from Sweden and Belgium. It demonstrates an international interest in brachytherapy and the potential application of the acquired knowledge.

11.1 Innovation

This thesis aims to improve brachytherapy treatment and can be divided into four specific novel subjects.

11.1.1 Model Based Dose Calculation Algorithm

AMIGOBrachy (A Medical Image-based Graphical platfOrm - Brachytherapy module) is software developed to create an efficient and powerful user-friendly graphical interface, needed to integrate clinical treatment plans with MC simulations. It does this by providing the main resources required to process and edit images, import and edit treatment plans, as well as set MC simulation parameters. It is the first software to provide all these functionalities combined with the capability to import and verify treatment plans created with commercial TPS (Treatment Planning System) through MC calculations. In addition, AMIGOBrachy can account for source movement, calculate different dose reporting quantities, mean energy and photon energy spectrum. All of these features are not currently available in typical clinical practice.

11.1.2 CAD-Mesh geometries

The modelling of complex brachytherapy applicators can be suboptimal when using voxel based geometry, due to the sub-voxel dimensions of specific components. In addition, applicator modelling using constructive solid geometry can be tedious, and may not allow complete fidelity or may be highly impractical, as is the case for deformable balloon applicators employed in accelerated partial breast irradiation (APBI).

Some modelling limitations can be avoided with CAD-Mesh geometries that can be imported by recent versions of general purpose MC codes. This thesis is the first study to evaluate CAD-Mesh models of brachytherapy applicators through MC simulations. Moreover, it is the most accurate method to model deformable applicators (APBI balloon applicator – item 4.3) available thus far.

11.1.3 Dose specification

Dose reporting quantities are especially relevant since the transition from the TG-43U1 formalism to more accurate dose calculation algorithms will make both $D_{m,m}$ and $D_{w,m}$ quantities available in typical clinical practice very soon. Differences between dose reporting in terms of $D_{m,m}$ and $D_{w,m}$ have been discussed in the literature with arguments in favor and against both quantities. However, this is the first study to show how differences in the photon energy spectrum inside of the patient can affect the relation between $D_{m,m}$ and $D_{w,m}$ for different tissues. This study can substantially contribute to future judgements regarding which quantity should be adopted as the standard in clinical practice.

11.1.4 Transit dose

The dose component due to source movement inside of the patient is, surprisingly, not well known. It is dependent upon the source speed profile which is not well established, with reported differences of up to a factor 10 (depending on the measurement methodology). Such large differences in the speed values lead to either negligible or highly significant transit doses, which was assessed for clinical cases for the first time in this thesis. These results indicate the importance to perform more accurate source speed profile measurements, which were conducted in this study for one afterloader model. Speed profiles were obtained using a high speed video camera capable of recording up to 960 fps leading to the most accurate source speed values available to date.

11.2 Clinical relevance

Patient safety is a priority for medical treatments with hospitals and research centers working exhaustively to improve the actual treatment conditions. However, brachytherapy is particularly prone to treatment errors, due to the lack of integrated imaging in the treatment room, coupled with the high dose gradients employed in the vicinity of radiosensitive healthy tissues and due to simplified dose calculation models. Furthermore, treatment plans obtained from commercial TPS are not commonly verified using alternative methods such as Monte Carlo. There is both a significant risk to underdose the tumor, and to overdose the healthy tissues.

The software developed, AMIGOBrachy (items 4.2 and 5.1), has a user friendly interface that can be readily adopted in clinical practice as an auxiliary dose calculation engine. It would provide an independent validation method with the possibility to account for applicators, tissues composition and densities. The clinical cases evaluated with AMIGOBrachy/MCNP6 show under and overdosing compared to TG-43U1 (item 4.2.4). The results obtained prompted the replacement of hollow cylindrical applicators at one hospital, due to a 5% target overdose concern in gynaecological cases. It was the first direct clinical application of this thesis and illustrates how treatment accuracy can be improved, sometimes, by adopting simple measures.

Finally, we provide a novel method to simulate deformable brachytherapy applicators (APBI balloon applicator – item 4.3) that cannot be modelled with conventional analytical geometry. The CAD-Mesh feature is also an alternative to model rigid brachytherapy applicators and may be a suitable option when the applicator model is provided by the manufacturer. Although the effect of the applicator can be significant (item 5.2), it is currently not taken into account by TPS based on the TG-43U1 formalism.

11.3 Societal relevance

The scientific findings discussed in this thesis can significantly improve dose calculation accuracy and provide relevant information that can be related to RBE effects and patient outcome. Therefore, in the short term, treatment plans can be more accurate by accounting for applicators, tissue composition, densities and other treatment complexities. In the longer term, different dose reporting quantities and mean energy or the energy spectrum can be assessed and related to patient outcomes once more data on these quantities becomes available.

Brachytherapy is widely employed worldwide due to good outcomes. However, the technology currently available can move the current standards towards even better outcomes. If translated into clinical practice, the developments achieved in this thesis would provide a significant contribution to this process.

Significant efforts were made to incorporate scientific advances into AMIGOBrachy so that they are available to the radiotherapy community. The study of different dose reporting quantities is an example of such an effort. Additionally, a physical discussion with quantitative values for dose reporting quantities were provided for a clinical case, the capability to score these quantities are part of AMIGOBrachy and can be used for any clinical case.

11.4 Commercial relevance

AMIGOBrachy may become part of a commercial product in the near future which would lead to revenue in the form of royalties, professional support service and training courses.