PhD Research Report

Treatment techniques for mixed-beam radiotherapy with simultaneously optimised photon and electron beams

Abstract

In radiotherapy, electron beams are well suited to the treatment of superficial targets while distally located organs at risk (OARs) are spared due to the dose fall-off. However, electron beams of conventional C-arm treatment units are limited to the treatment of targets within five cm of the patient surface owing to their limited range for available energies up to 22 MeV. Moreover, OARs that are located laterally to the target relative to beam direction cannot be spared adequately due to the large penumbra of the electron beams. In contrast with electron beams, photon beams have very small penumbra and targets can be treated at all locations in the patient because the dose falls off exponentially. However, this exponential fall-off also leads to the delivery of a large dose to normal tissue. A treatment approach that mixes the beams, called mixed-beam radiotherapy (MBRT), could merge the advantages of the uses of photons and electrons while keeping their downsides to a minimum. This study hypothesises that there is a high potential for the treatment of targets that involve at least one superficial part. Thus, the aim of the work that is described in this thesis was to develop and investigate treatment techniques for MBRT with simultaneously optimised photon and electron contributions that could be delivered efficiently and accurately by use of a conventional C-arm treatment unit.

The study suggests the use of the photon multileaf collimator (pMLC) to collimate the electron beam instead of cut-outs that are usually placed in the electron applicator. This technique improves the efficiency of electron treatments and facilitates use of advanced treatment techniques for modulated electron radiotherapy (MERT) and MBRT. The study shows that today's single-electron-field treatment plans that use cut-out collimation can be replaced by plans of similar treatment-plan quality by use of pMLC collimation with accurately calculated dose distributions at a large source-to-surface distance range of 70-100 cm. Next, the impact of intensity and energy modulation that is enabled by the pMLC is investigated for MERT plans of the breast, skin, parotid and larynx. Energy modulation is found to be of substantially larger value than intensity modulation to increase treatment plan quality for MERT.

To explore the dosimetric potential of MBRT, a treatment planning process (TPP) is developed that enables the generation of pMLC-based step-and-shoot MBRT plans (ssMBRT) with simultaneously optimised and Monte Carlo (MC) calculated photon and electron contributions. The development of a simulated annealing-based direct aperture optimisation is described and it is applied for the purpose of simultaneous optimisation. The ssMBRT plans that are generated for a left chest wall and a head and neck case are shown dosimetrically to outperform plans for MERT, photon intensity-modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT).

Besides electron beams, conventional C-arm treatment units also offer other degrees of freedom (DoFs), which are not utilised with current state-of-the-art treatment techniques. Thus, a non-coplanar treatment technique for dynamic trajectory radiotherapy (DTRT) has been developed in our research group. It utilises combined dynamic gantry, table and collimator rotations during the beam-on period of a photon beam. For several cancer cases (two head and neck, one lung, one oesophagus and one prostate), it is shown in the study that DTRT improves treatment-plan quality compared with VMAT. The combination of photon dynamic trajectories with step-and-shoot modulated electron beams, called dynamic mixed beam radiotherapy (DYMBER), results in a treatment technique that utilises more DoFs than any other treatment technique that has been presented before for conventional C-arm treatment units. Thus, a TPP is developed to enable the creation of DYMBER plans. This TPP is applied to a brain and two head and neck cases and the resulting DYMBER plans are found to be dosimetrically superior to DTRT and VMAT plans. Furthermore, MC-calculated dose distributions of the DYMBER plans agree very well with absolute dose measurements that are performed with Gafchromic films placed in an anthropomorphic phantom.

In conclusion, this thesis demonstrates the dosimetric value of combining particle types for radiotherapy for the case of photons and electrons. The results of the efficiently and accurately deliverable MBRT plans suggest that the use of MBRT for future clinical applications to treat targets that contain at least a superficial part of any treatment site leads to improved treatment-plan quality compared with photon-only techniques.

What was the motivation for the topic of your PhD work?

In the first paragraph of the abstract, the dosimetric characteristics of photons and electrons are compared. There we see that the beams of these two particle types are fundamentally different. However, they are rarely combined these days and only with simple 3D conformal irradiation techniques. The big question therefore is: how well and with what approach could we exploit the different dosimetric characteristics of photons and electrons to further improve plan quality? We hypothesised that a large dosimetric benefit of simultaneously optimised photons and electrons could be acquired compared with state-of-the-art techniques such as IMRT and VMAT.

What were the main findings of your PhD work?

We demonstrated that we could generate accurately and efficiently deliverable mixed photon and electron plans (either ssMBRT or DYMBER) that dosimetrically outperformed sophisticated photon-only plans. As an example, the use of DYMBER decreased the mean dose to parallel OARs by 28% and the near maximal dose to serial OARs by 37% over VMAT averaged over three cases in the brain and head and neck regions. The following three aspects were the key to this demonstration:

1. Simultaneous optimisation of photon and electron contributions to exploit the different characteristics of the particles.
2. Usage of the pMLC for both particle types to enable intensity and energy modulation for electrons with an efficient delivery manner and to switch comfortably between the two particle types without the clinician being required to enter the treatment room.
3. Usage of MC simulations to predict the dose accurately. The electron beams in particular pose a challenge due to their pronounced scattering behaviour.

Can you comment on the impact of your work to the field?

Based on our results, the radiooncology community might recognise the value of electrons in an advanced combined photon and electron setting. In our opinion, the most important step that is required to introduce an advanced mixed-beam technique is first to replace the current applicator/cut-out solution with a pMLC solution for standard electron treatments. We believe that treatment unit vendors will be increasingly motivated to make this step, not only to open the door for advanced mixed-beam techniques, but also to ease clinical workflow and to reduce the number of hardware devices that are required (i.e. electron applicators). The motivation is similar to that which led to the replacement of blocks with the MLC in the case of photon beams more than two decades ago. Photon treatments became more efficient and intensity modulation was enabled.

Moreover, we demonstrate through this work the plan quality of which the current C-arm treatment units are capable if we exploit more DoFs. DYMBER is a good example of this. This could offer strong motivation to vendors to implement such treatment techniques to exploit further the potential of the already installed treatment units. By this method, reduced side effects can potentially be achieved in radiotherapy.

What was the most challenging part of your PhD?

The part that considered development and investigation of DYMBER was definitely the most challenging part, due to the following two required tasks:

1. The development of a treatment planning process that exploited all the DoFs provided for DYMBER (see Figure 1) within reasonable calculation times. The search space for optimisation of all the plan parameters is enormous. The heuristic that was required to determine the gantry-table and gantry-collimator paths a priori to intensity modulation was the key to the handling of the DoFs.
2. The validation of MC-calculated DYMBER dose distributions with EBT3 film in an anthropomorphic phantom in absolute dose units. Many aspects must be considered accurately when treatment plans of a novel treatment technique are delivered: does the dose calculation consider all important impacts such as MLC scatter and couch absorption? How well does the beam model represent the specific treatment unit? How safe is the collision avoidance?

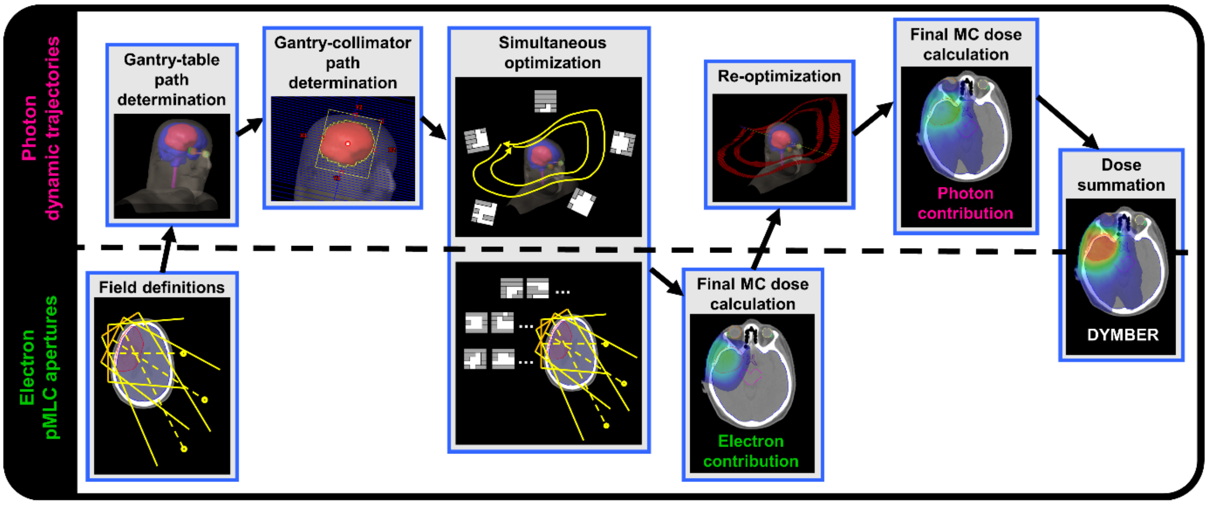

Figure 1: The treatment planning process that was developed to generate DYMBER plans. Figure taken from Mueller et al. [5]. © American Association of Physicists in Medicine. Reproduced with permission of Wiley. All rights reserved.

Who or what inspired you most during your studies?

The exploration of the results of simultaneously optimised photon and electron beams was very exciting. How well will mixed beams perform dosimetrically compared with established techniques such as IMRT and VMAT? What treatment site can benefit from the use of electrons? Which part of the target is covered by which particle type? Questions like these ignited my passion for this research topic (Figure 2 gives some illustration).

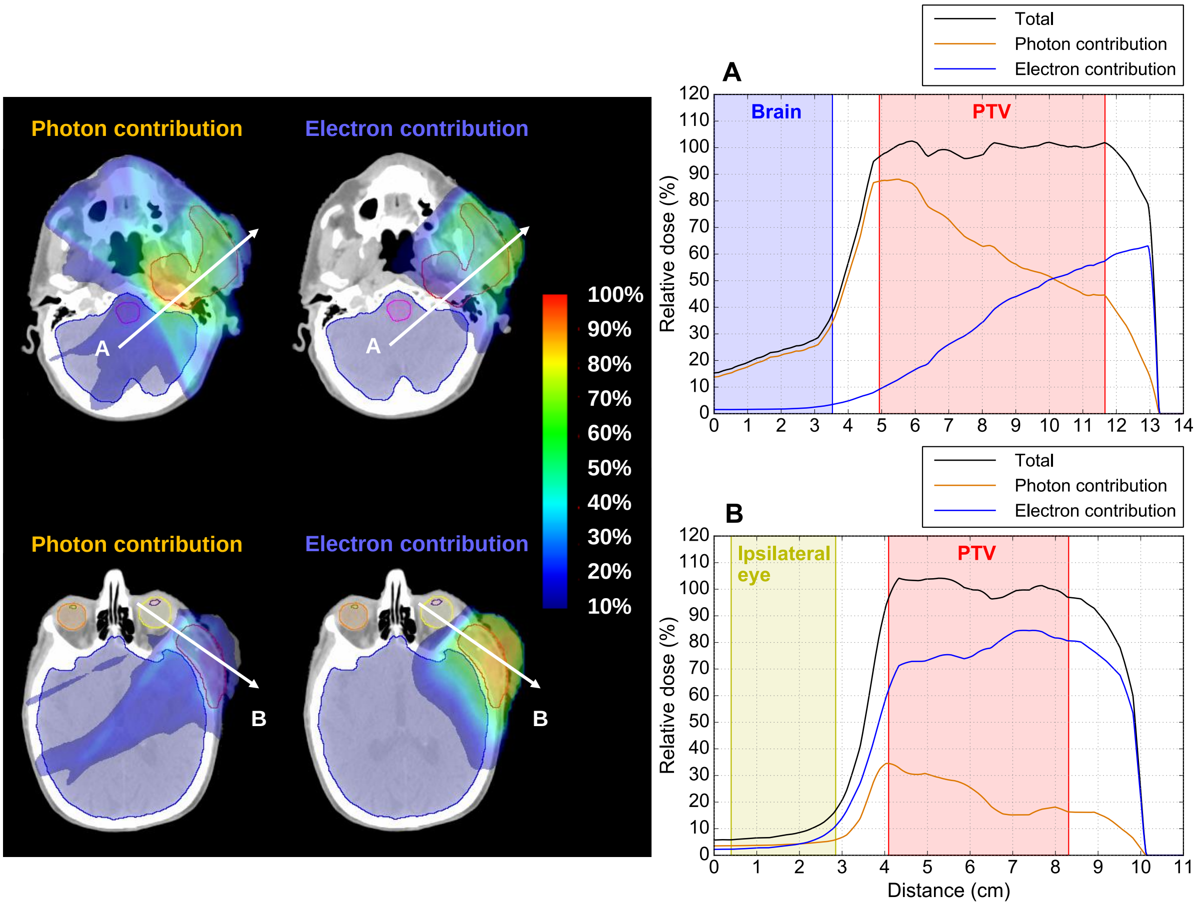

Figure 2: Dose distributions (left) and dose profiles (right). A and B show the photon and electron contributions of an ssMBRT plan for a head and neck case. Profile A demonstrates that the deep-seated part of the planning treatment volume (PTV) is mainly covered by photons, while dose profile B shows that a superficial part of the PTV that is surrounded by OARs is

dominantly covered by electrons. Figure taken from Mueller et al. [3]. © Institute of Physics and Engineering in Medicine. Reproduced with permission of IOP Publishing. All rights reserved.

Another important inspiration was offered through the brainstorming sessions with my main advisors, Dr Peter Manser and Professor Michael Fix, that considered the research question we wanted to answer and how to point out the key messages of our work. These discussions were the origin of many fruitful ideas. The value of such discussions became even more apparent to me in the last few months while I was working at home due to the coronavirus situation. Generally, the working atmosphere at the Division of Medical Radiation Physics and the Department of Radiation Oncology at the Inselspital Bern was inspiring, as I was frequently in contact with all kind of professionals in our field including physicists, technicians, radiooncologists, radiotherapists and others. Getting to know the point of view of all these professionals and the diverse aspects of their work was very valuable in the development of a novel treatment technique.

Will you stay in the field? What are your plans for the future?

Yes. Since I finished my PhD thesis, I have been working as a post-doctoral fellow in the same division to continue the research about the treatment techniques of DTRT and DYMBER. The content is two-fold. On one side, we want to explore the potential for further dosimetric and practical improvements of DTRT and DYMBER. Examples are the addition of more DoFs such as table translations for treatments of large targets or further plan optimisation to increase robustness against patient and machine uncertainties. On the other side, we continue to develop DTRT and DYMBER in the direction of clinical applications.

Which institution were you affiliated to during your PhD?

I matriculated at the ETH Zurich (Swiss Federal Institute of Technology, Zurich) and I carried out the work for the thesis at the Division of Medical Radiation Physics, Inselspital, Bern University Hospital, both in Switzerland.

When did you defend your thesis and who was your supervisor?

The defence was held on 7 November 2018 with the examination committee, which consisted of my supervisor Professor Marco F. M. Stampanoni and the co-examiners Dr Manser and Professor Paul J. Keall.

About the author

Silvan Mueller completed an apprenticeship in information technology in 2007. He received his Bachelor in Physics degree in 2013, his Master in Physics in 2015 and his Master of Advanced Studies in Medical Physics in 2018 from the ETH Zurich. In 2019, he received his PhD degree from the ETH Zurich.

His research activities involve the development of novel treatment techniques for radiotherapy to improve dosimetric plan quality, practicability, efficiency and accuracy. His PhD work was about development of treatment techniques for mixed-beam radiotherapy with simultaneously optimised photon and electron beams. He is currently employed as a post-doctoral fellow at the Inselspital Bern and is focused on a project that considers efficient and robust optimisation of DTRT and DYMBER.

The results of his PhD thesis have been published in high-ranked medical physics journals [1-5]. The publication about simultaneous optimisation of photons and electrons for MBRT [3] was the editor's choice of the corresponding issue in Physics in Medicine & Biology. In addition, the abstract of the preliminary work of the publication about DYMBER [5] in medical physics received the best in physics award at the 59th annual meeting & exhibition of the American Association of Physicists in Medicine (AAPM) in 2017.

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