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Overview

Image Guidance for Proton Therapy

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Abstract

Image-guided radiotherapy has an established role in all forms of radiotherapy treatment delivery. Proton therapy seeks to deliver superior dose distributions through utilising the Bragg peak to target tumour and avoid sensitive normal tissue. The Bragg peak and sharp falloff in dose delivered by proton therapy necessitate careful treatment planning and treatment delivery. The dose distribution delivered by proton therapy is particularly sensitive to uncertainty in the prediction of proton range during treatment planning and deviations from the planned delivery during the course of the fractionated treatment. Realising the superior dose distribution of proton therapy requires increased diligence and image guidance has a key role in ensuring that treatments are planned and delivered. This article will outline the current status of image guidance for proton therapy, particularly highlighting differences with regard to high-energy X-ray therapy, and will look at a number of future improvements in image-guided proton therapy.

Keywords: Image guidance; Proton

Introduction

Radiotherapy in all its forms involves depositing a potentially lethal dose of radiation to the tumour to cure patients of cancer. In external beam therapy, where radiation beams are targeted from outside the patient, delivering the prescribed dose to the defined target volume while sparing surrounding normal tissue is of upmost importance. In practice the accurate and precise delivery of radiotherapy throughout a course of treatment requires technical treatment planning, to identify disease and target the radiation dose, along with on-treatment monitoring to ensure the patient is treated as planned. Imaging in many forms is a key tool used in both treatment planning and treatment delivery. The term 'image-guided radiotherapy' is often defined as the use of imaging at the pretreatment and treatment stage that leads to an action to improve or verify the accuracy of radiotherapy [1]. This article will examine the difference in image guidance for proton therapy and high-energy X-ray therapy for both treatment planning and treatment delivery.

The advantage of proton therapy through the delivery of dose by the Bragg peak is well known. To utilise this advantage in terms of patient outcome, particular attention must be applied to predicting the range of the proton beam at which the Bragg peak delivers its dose, during pretreatment planning and during treatment delivery. In the pretreatment planning, imaging is required for target and normal tissue delineation and also as the basis for the dose calculation to assess where the Bragg peak delivers its dose. During the delivery of fractionated radiotherapy, anatomical changes in the patient in proton therapy alter the position of the Bragg peak and change the dose distribution, potentially leading to dose inhomogeneity in the target and/or overdose of normal tissue.

There are differences between proton and high-energy X-ray therapy that lead to image guidance being used in different ways. In treatment planning there is additional difficulty in using computed tomography (CT) images in dose calculation algorithms for proton therapy. In the treatment room, cone beam CT and full diagnostic CT are beginning to be used, but developments have been slow

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compared with other forms of radiotherapy. There are also additional modes of imaging associated with directly imaging the dose deposition of protons that are termed ‘range verification’ and in the future the proton community is looking towards the advantages of imaging with the proton itself.

Imaging for Treatment Planning

Many imaging modalities used in treatment planning for proton therapy are the same as those used for conventional radiotherapy, and in many of the steps of the planning process, for instance volume delineation, imaging systems, such as CT, magnetic resonance imaging and positron emission tomography (PET), can be used in the same manner for proton therapy as they are for high-energy X-rays.

However, there are differences in the way that images can be used in proton therapy treatment planning. The primary imaging modality in radiotherapy is the CT scan and it is used to provide anatomical information on the patient and also as the primary image upon which a dose calculation can be made. To allow a CT image to be used in a dose calculation, the Hounsfield units (HU) that form the CT image must first be used to derive other parameters. In high-energy X-ray therapy, HU are related to electron or physical density, which are the parameters required to allow the calculation of the dose deposited by megavoltage photons. In proton therapy, the HU must be converted into proton stopping powers before the dose calculation can be carried out. The process of deriving stopping powers from HU is complex, as it aims to predict the behaviour of one type of particle (the proton, a charged particle) from the behaviour of a completely different particle (the massless, chargeless photon used to acquire the kilovoltage CT image). There is, therefore, an uncertainty associated with the derived stopping powers, which is consequently a source of uncertainty within the dose calculation itself. The conventional method for calibrating a CT scanner for proton therapy is the stoichiometric method [2], which is a two-step process. In step one, the scanner is characterised by taking scans of tissue substitute materials with known compositions and parameterising the relationship between the measured HU and the material properties. In step two this parameterisation is applied to a set of published reference tissue compositions, to generate a relationship between the stopping powers (as calculated from the tissue composition) and the associated HU values (as calculated from the relationships derived in step one). As noted, this calibration is more complex than that for high-energy X-rays and more than one calibration curve may be required, for instance for different sizes of patient. Given the importance of range in proton therapy, a final check of proton range in real animal tissue imaged on a CT scanner is often made.

Even with great care, the stoichiometric method of calibration still results in uncertainty in the proton dose calculation, and the related prediction of proton range. It is for this reason that there is considerable interest in dual-energy CT for proton therapy. Although proton therapy is not the prime motivation for the commercial development of dual-energy CT, the ability of scanners to improve tissue characterisation has the potential to improve the estimation of proton stopping powers and is of great interest. The degree of improvement is the topic of much current research [3] and depends on a number of factors, including the design of the dual-energy scanner, the particular method used to determine stopping power from the dual-energy imaging and the implementation of dual-energy scans in the treatment planning system. However, several researchers have reported a clinically significant reduction in range uncertainty and incorporating dual-energy CT scans into treatment planning systems will allow this to be realised clinically.

Kilovoltage Imaging for Patient Set-up

Proton therapy was an early implementer of image guidance in the treatment room. The increased dosimetric consequence of changes in patient position necessitated in-room imaging to verify patient set-up on a daily basis. In the early implementation of proton therapy this was achieved through the greater use of kilovoltage imaging in the treatment room. Kilovoltage imaging systems have been routinely used in conjunction with fixed beam and gantry-based proton therapy treatments. Typically, two-dimensional kilovoltage imaging would be used before delivery of the treatment field. A two-dimensional kilovoltage image taken at set-up can be compared against a digital reconstructed radiograph produced from the planning CT scan [4]. The angles for verification must be chosen at the planning stage. Often the angles will correspond to the beam directions, but other angles may be chosen specifically to assist with patient set-up.

In addition to the patient position on the couch, particular attention must be paid to the position of bony anatomy such as the pelvis, as this will affect the range on the proton field. Kilovoltage imaging is an effective way to ensure that the patient is in as similar position as practicable to that in which the proton therapy treatment plan was prepared. However, two-dimensional kilovoltage imaging has an inherent limitation, in that it is difficult to assess the effect of anatomical changes that occur during treatment on the planned dose distribution.

Volumetric Imaging in the Treatment Room

To a certain degree, X-ray therapy was image guided before the evolution of volumetric imaging in the treatment room. For many years, megavoltage imaging was used in the treatment room to correct patient set-up and some stereoscopic kilovoltage imaging systems were used clinically [5]. However, it was the advent of volumetric CT imaging in the linear accelerator bunker that sparked the revolution of image-guided radiotherapy. Volumetric imaging in the

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