Commentary

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Dosimetric Impact of Patient Movement in Proton Therapy

Abdulaziz Abolaban*

Department of Radiation Oncology, University of Medical Center Groningen, Groningen, The Netherlands

Corresponding author: Abdulaziz Abolaban, Department of Radiation Oncology, University of Medical Center Groningen, Groningen, The Netherlands, E-mail: abdulaziz@gmail.com

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Description

Proton therapy, an advanced form of radiation therapy, offers a high degree of precision by targeting tumors with protons rather than traditional X-rays. Its main advantage lies in the unique physical properties of protons, which deliver the maximum dose at a specific depth in tissue known as the Bragg peak, sparing surrounding healthy tissues from excessive radiation exposure. However, one of the challenges in proton therapy is patient movement during treatment, which can significantly affect the accuracy of dose delivery. This article discusses the dosimetric impact of patient movement in proton therapy and describes various strategies for mitigating these effects to improve treatment efficacy and patient outcomes. Proton therapy's precision relies on the stable and predictable positioning of both the patient and the tumor. However, the precision that makes proton therapy so effective also makes it sensitive to movement, especially as it targets specific tissue depths. Unlike photons, which penetrate tissue more uniformly, protons have a well-defined range where they deposit most of their energy any movement can alter where this energy peak, or bragg peak, falls within the body. Even slight shifts can misalign the bragg peak, leading to an insufficient dose to the tumor or unintended irradiation of nearby healthy tissues. Movement can be voluntary, such as patient positioning shifts, or involuntary, such as respiratory motion. Movement is particularly problematic in treating tumors in areas like the lungs or liver, where breathing causes frequent and complex positional changes.

Dosimetric consequences

Under-dosing of tumor tissue: If a tumor shifts out of the targeted Bragg peak area due to movement, the intended dose may fall short, resulting in under-dosing. This insufficient exposure can compromise treatment efficacy, as cancer cells may survive and continue to proliferate.

Over-dosing of surrounding healthy tissue: When movement shifts the proton beam's target area, healthy tissue surrounding the tumor may receive unintentional radiation. This can lead to increased toxicity, adverse side effects and damage to critical structures adjacent to the tumor.

Compromised dose distribution: Patient movement can distort the intended dose distribution, leading to non-uniform dosing across the tumor. This inconsistent dose distribution can reduce Tumor Control Probability (TCP), as certain tumor areas may receive lower doses than required to control or eliminate the cancer cells effectively.

Tumor location: Tumors in organs that move during normal physiological processes, like respiration or digestion, are more susceptible to movement-related dosimetric issues. For example, liver and lung tumors pose greater challenges due to their constant displacement with each breath.

Patient positioning and comfort: Optimal patient positioning and immobilization are vital for reducing voluntary movement. Uncomfortable or awkward positions can lead to shifting as patients adjust themselves during treatment.

Beam modulation

The beam's angle and modulation can influence susceptibility to motion effects. Techniques such as pencil beam scanning are more sensitive to movement due to their targeted, layer-by-layer approach, which can amplify the impact of shifts if the beam fails to align accurately with the moving target.

Image-guided proton therapy: IGPT involves imaging the patient in real-time or just before proton beam delivery, allowing clinicians to adjust the beam’s angle and positioning to accommodate any movement. Techniques like Cone-Beam Computed Tomography (CBCT) and MRI-guided proton therapy provide improved imaging for better alignment. By identifying the tumor's exact location, IGPT minimizes errors due to patient movement, increasing dose accuracy.

Respiratory-gated proton therapy: Respiratory gating synchronizes beam delivery with the patient's breathing cycle. Sensors detect the breathing pattern and the proton beam is only activated at specific points in the cycle when the tumor is in the intended position. This approach is particularly effective for tumors in the thoracic and abdominal regions, as it allows dose delivery at times when movement is minimal, reducing the chance of misaligned dosing.

Breath hold techniques: Patients can be instructed to hold their breath during short-duration treatments to limit respiratory motion. Techniques like Deep-Inspiration Breath Hold (DIBH) stabilize the tumor's position by immobilizing the chest. Although challenging for some patients, breath-hold techniques are effective in minimizing movement and enabling precise targeting.

Treatment planning and simulation: Four-dimensional (4D) treatment planning incorporates time as an additional dimension, capturing the tumor's motion throughout the respiratory cycle. By simulating how the tumor moves in 4D space, clinicians can adjust the treatment plan accordingly, customized it to accommodate positional changes due to breathing.

Motion-adaptive proton therapy: Motion-adaptive therapy actively adjusts the beam to follow the tumor’s movement in real-time. Using a combination of tracking technologies and dynamic beam control, this approach allows for continuous adjustment of the proton beam’s trajectory, ensuring accurate dose delivery despite ongoing motion. This technique is still under development, with recent advances in real-time imaging and adaptive systems offering promising results.