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Influence of the distal fall-off on the biological effective proton range

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Introduction: For the application of protons in radiotherapy a constant relative biological effectiveness (RBE) of 1.1 is considered in the treatment planning procedure. However, the results of in-vitro experiments [1, 2] show an increase of the RBE towards the distal end of a proton spread out Bragg peak (SOBP). RBE predictions of the local effect model (LEM IV; [3]) are consistent with these experimental data [5]. Due to the fact that the LET is further increasing in the declining edge of the SOBP the RBE is higher than the clinically used value of 1.1. As a consequence, this increased RBE leads to an extension of the biologically effective proton range. In the presented work we investigate the influence of the physical dose fall-off on the RBE and the biologically effective range of the proton beam.

Methods: Since the most distal proton Bragg peak that contributes to the proton SOBP determines the gradient of the dose fall-off, the treatment planning software TRiP98 [4] was used to calculate the physical and RBE-weighted depth dose distribution of monoenergetic proton Bragg peaks with energies ranging from 71 to 220 MeV. With increasing initial energy of the proton beam the distal dose fall-off gets broader, i.e. the gradient increases, due to range straggling in the absorber material. The corresponding RBE-weighted dose was calculated based on the RBE predictions of the LEM IV. The biological range extension and the RBE at maximum RBE-weighted dose were investigated for different dose-levels of 1-10 Gy absorbed dose and two different α/β-ratios of 2 Gy and 10 Gy, respectively. The biological range extension is defined as the difference of the RBE-weighted doses based on a constant RBE of 1.1 and the LEM IV based RBE at the 80 % isodose.

Results: Figure 1a illustrates the RBE at maximum RBE-weighted dose in the SOBP in dependence on the gradient of the 80-20 % dose fall-off. The RBE at maximum RBE-weighted dose is decreasing with increasing gradient of the distal dose fall-off. In contrast, the biological range difference is increasing with the flattening of the distal dose fall-off (fig. 1b). Further, the RBE and thus the biological range difference is larger for α/β-ratios of 2 Gy compared to 10 Gy and decreases with increasing dose [5]. The results show that the the gradient of the distal dose fall-off opposingly affects the RBE-weighted dose at the distal end of the SOBP and the biological range extension of the proton beam.

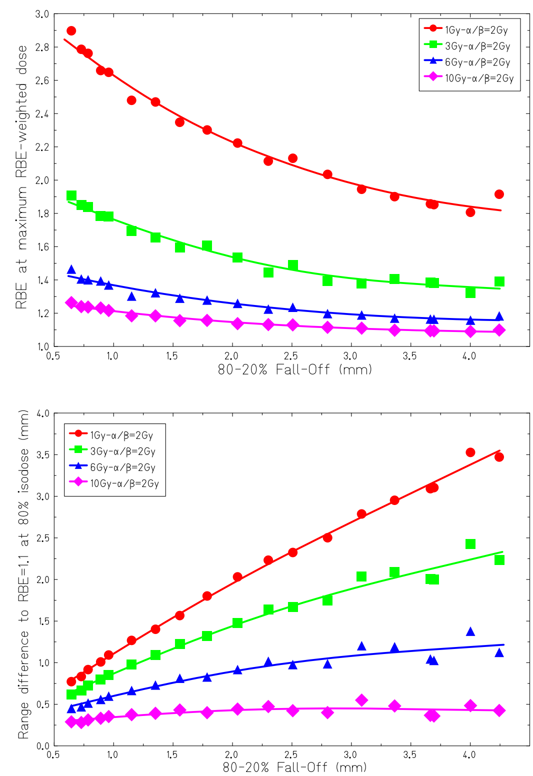

Figure 1: RBE at maximum RBE weighted dose (a) and biological range difference (b) in dependence on the distal penumbra for a α/β-ratios of 2 Gy and different physical dose levels of 1, 3, 6, and 10 Gy. The data points represent the distal fall-off for energies from 71 to 220 MeV.

Conclusion: The increasing RBE at the distal end and the biological range extension are influenced by both biological factors like the α/β-ratios of the cell or tissue type and physical factors like the gradient of the distal dose fall off. Hence, the initial beam energy and the depth modulation system used to create the SOBP mainly affect the balance between maximum RBE-weighted dose and biological range extension.

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