COMPARISON OF BIOLOGICAL IMPACT OF PROTON AND ION BEAMS IN RADIATION TREATMENT

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Abstract

The work contains the comparison of biological doses' distribution calculated for treatment of the same targets by proton and ion beams. Advantages of the ion beam are shown for targets with different sizes and with different depths.

We made an attempt to compare the distribution of the biological dose for treating same targets with proton and ion beams. The research [1] based on the calculations performed with TRIM program [2] contained the evaluation of the integral distribution of the physical dose D and biological dose BD = D * RBE in water environment with a single-direction irradiation using the target scan with the thin beam for different target sizes (a cylinder with the diameter d and the size along the beam d) and with varying depth within the body L. The number of layers for the scanning was determined by the allowance for the consistency of irradiation (±5%). It was assumed for the calculation purposes that the beam has impulses' discrepancy of dP/P = ±0.5% (where P is the particle's impulse), the initial angle divergence (±2 mrad), the lateral dimensions equal to the size of the target (in accordance with the target's scan) and that it is directed at a patient with such variable energy that Bragg's peak would be at a depth of the layer required for the irradiation. The calculations included the particles' diminution caused by the nuclear interaction, the impact of repeated Coulomb's dispersion, the statistical dispersal of range's size and the dependency of relative biological efficiency RBE of particles with the given energy at the current depth within the body.

This dependency is not known authentically. The amount of RBE strongly depends on dE/dx [KeV/mkm], from the type of cells, from the organ that is being irradiated, from the method of measurement and from the size of a single dose. The curve shown on Figure 1, taken from the source [3] and from Figuress 1.2, 4.1, 4.2 and from source [4] was used to evaluate the amount of RBE, depending on dE/dx.

The calculations were made for the target sizes d from 1cm to 16cm with the depth of target's deposition from L≥ 1cm to (L+d)=30 cm. The research [1] shows that the basic distribution of the integral BD in relation to depth can be approximately (with the accuracy of ±10%) described as a constant in the target (BD = 1.0) and as a plateau until the target with BD= K, with the transitional zone of 3 cm (see table 1 and Fig. 2). Tailings in the zone's distribution, which appear during ions' fragmentation, were not accounted for.

Additionally, there are zones of irradiation on the side of the target, related to the secondary particles' dispersion in the body, and beyond the target, related to particles' scattering within the beam with impulses dP/P and with the statistical dispersion of ranges. The sizes of these zones depend on the depth and can be estimated through the calculations utilizing the THRIM program.

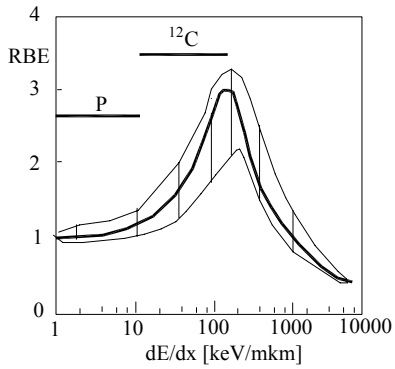

Figure 1: Dependence of RBE from dE/dx.

Table 1. The evaluation of K (the relation of BD on the plateau until the target to BD in the target), depending on the target's size, during target's irradiation in the water environment, using the single-direction scanning with ion and proton beams.

Target cylinder, diameter d [cm]; its size d in depth	1	2	4	8	16
Protons K	0.55 ±0.10	0.60 ±0.10	0.70 ±0.08	0.80 ±0.07	0.95 ±0.05
Carbon ions K	0.28 ±0.05	0.38 ±0.05	0.51 ±0.05	0.70 ±0.05	0.95 ±0.05

Ion beams additionally irradiate the healthy tissues behind the target. This is related to potential nuclear interactions and with the possible disintegration of ions into charged particles and neutrons (fragmentation). Newly created particles have varying directions and energies, which is why they don't have the maximum energy release at the same place, where the initial ions have Bragg's peak. The distribution of the physical dose beyond Bragg's peak was calculated and measured multiple times (Fig. 2 [5]). The lower the depth of the target is, the smaller are the ranges of the ions, the less nuclear interactions take place. For the depth of 30 cm, the level of the physical does immediately beyond the target's volume is 15% of the does within the target, lowering with the depth. This means that the level of the biological dose beyond the target is always below 8% from BD within the target, due to fragmentation.

ISBN 978-3-95450-170-0

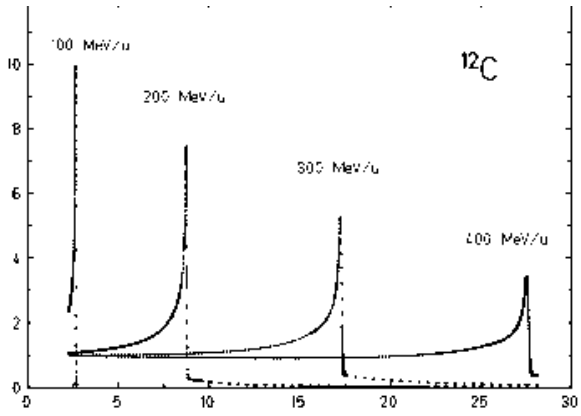

Figure 2: Examples of distribution of physical dose along the direction of carbon ions' beam, depending on their energy (MeB per one nucleon) [5].

There is a dependence of the biological impact on the irradiated cells from the biological dose. This dependence is shown schematically on Fig. 3 for three different types of cells. Two important data points are visible on all graphs. The first one is BD1, which indicates the 90% probability of suppressing cells' life (and higher with increased doses). This level is used during the therapy. With lower doses, the probability of suppression is reduced in an approximately linear pattern; in data point BD2, it becomes around 10%. With even lower doses, the probability of suppression is reduced more flatly and the irradiation virtually doesn't suppress the cells [5].It's important to notice that the ratio of doses in points BD1and BD2 does not exceed 5 and that the lower is Bragg's peak depth, the lower is the impact of fragmentation. Therefore, the impact of fragmentation is not high for the evaluation of the biological dose distribution beyond the target with the 15% accuracy, despite the significant space being irradiated [5].

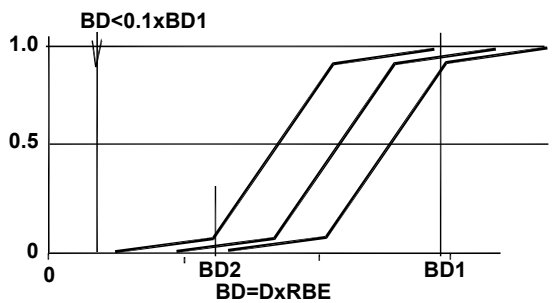

Figure 3: The dependence of the biological impact from the biological dose.

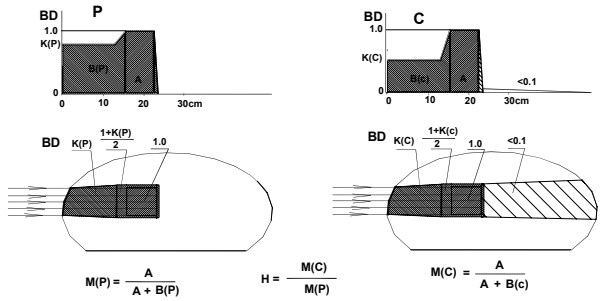

Figure 4: The scheme of the distribution of the biological dose BD for the irradiation of the target with size d, which is positioned on depth L.
A – Useful integral BD within the target;
B – Harmful integral BD emitted by the beam within the body outside the volume of the target;
(A+B) - total integral biological dose emitted by the beam in the body;
M=A/(A+B) – the share of the useful biological dose within the total biological dose emitted by the beam in the body;
H = M(C)/M(P) – by how many times the ion beam distributes the biological dose in a more useful way.

In order to get the same therapeutic effect using proton and ion beams, the target should be irradiated with the same biological dose. The integral of the biological dose within the target is labeled A, while the integral of the biological does outside the target is labeled B. The size of B depends on the particles' type – protons B(P) or ions B(C). It is suggested to characterize the quality of irradiation by the relation of M(P)=A/(A+B(P)) and M(C)=A/(A+B(C)), the integrals of the biological dose A distributed within the target (the useful effect of the beam), to the total biological dose emitted by the beam in the body – A+B(p) for the protons and A+B(C) for the ions. Correlation H = M(C)/M(P) indicates by how many times the application of the ion beam is more effective than the use of the proton irradiation with the same targets. The results of the calculations are presented in table 2. It's obvious that this correlation will be close to 1,0 for the irradiation of surface targets (L=0), without taking into consideration beam's scattering within the target.

Because the accuracy of estimating the distribution of BD in relation to depth was close to ±10% [1], the accuracy of the calculations being conducted does not exceed ±15%, but they do provide the general understanding of the degree to which the use of more expensive ion beams, instead of traditional proton beams, is justified.

Similar estimates can be used for the multi-directional irradiation of a target, setting a specific target depth L for every direction and the size of a target in a given direction d.

ISBN 978-3-95450-170-0

Table 2. Comparison of the biological impact of ion and proton beams for different target sizes and depths.

L см **d** см		1	2	4	8	12	18	26
1	M(P) M(C) H	**0.51** **0.59** **1.2**	**0.35** **0.42** **1.2**	**0.23** **0.30** **1.3**	**0.14** **0.22** **1.5**	**0.10** **0.17** **1.7**	**0.07** **0.13** **1.9**	**0.05** **0.10** **2.0**
2	M(P) M(C) H	**0.64** **0.72** **1.1**	**0.50** **0.57** **1.1**	**0.36** **0.43** **1.2**	**0.24** **0.32** **1.3**	**0.18** **0.25** **1.4**	**0.13** **0.19** **1.5**	**0.10** **0.15** **1.5**
4	M(P) M(C) H	**0.76** **0.82** **1.1**	**0.63** **0.70** **1.1**	**0.50** **0.57** **1.1**	**0.36** **0.43** **1.2**	**0.28** **0.35** **1.2**	**0.21** **0.28** **1.3**	**0.15** **0.20** **1.3**
8	M(P) M(C) H	**0.82** **0.88** **1.1**	**0.74** **0.80** **1.1**	**0.63** **0.69** **1.1**	**0.49** **0.55** **1.1**	**0.40** **0.46** **1.1**	**0.32** **0.37** **1.2**	
12	M(P) M(C) H	**0.84** **0.90** **1.1**	**0.79** **0.81** **1.1**	**0.70** **0.75** **1.1**	**0.57** **0.62** **1.1**	**0.48** **0.53** **1.1**	**0.39** **0.43** **1.1**	
16	M(P) M(C) H	**0.86** **0.92** **1.1**	**0.81** **0.87** **1.1**	**0.73** **0.79** **1.1**	**0.62** **0.66** **1.1**	**0.53** **0.57** **1.1**		

CONCLUSION

Table 2 shows that the ion beam always irradiates healthy tissues less then the proton beam. This advantage is significant for deep targets (L≥ 4cm) with small sizes (d≤ 4cm). However, despite the sharper Bragg's peak, up to 3 times higher RBE (in maximum of dE/dx) and 20 times higher LET of ions, for many targets, the difference between the quality of irradiation with ion beams and with proton beams is small – below 10%.

These conclusions could be expected, based upon several basic characteristics of BD distribution in water by proton and ion beams. First: the bigger is the target size d, the closer is the BD plateau before the target K to the dose within the target (see [1] and table 1) and the difference between the application of the ion beam and the proton beam is reduced. Second: the smaller the depth of the target is, the lower is the volume of health tissues that are being irradiated, and the closer are the results of proton and ion irradiation. Third: the bigger the depth of the target L is, the higher is the impact of healthy tissues' irradiation due to the repeated Coulomb's scattering, especially, for small targets. Ions' angles of scattering are 4 times less than those of protons.

The presented estimates may be useful for a rough comparison of multi-directional irradiation plans, where L and d values can be determined for every direction, and also for the planning of the new ion and proton irradiation centres' development.

It is very useful to repeat those calculations with more high precision by using well known system for planning of irradiation.

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ISBN 978-3-95450-170-0