The relative biological effectiveness of proton and ion beams

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Abstract

The understanding of the biological effectiveness of proton and ion beams plays an important role in two very different scientific fields: radiotherapy and space research. Due to the many similarities of both types of radiation, the question is addressed, if the experience gained in radiotherapy with proton and ion beams is of relevance for the assessment of risks due to galactic radiation in manned space flight. The basic characteristics of the relative biological effectiveness (RBE) of proton and ion beams is reviewed, including the dependence on particle type, LET and dose as well as on biological systems and end points. The relevance of these factors for risk assessment in space flight is outlined. The concept of clinical RBE is reviewed and the RBE database gained in vivo is briefly outlined. Emphasis is put here on the most important endpoint for radiation protection, which is carcinogenesis. The database for risk assessment due to galactic cosmic rays is nearly completely based on animal experiments conducted at ion beam therapy facilities. The data especially for carcinogenesis due to heavy ions are very scarce and the estimation of risk factors is connected to large uncertainties. The database gained by the clinical application of ion beams is still too limited to draw any direct conclusion for space research. This may change in the next decade due to the increasing patient numbers that will be treated in the new ion beam facilities. Until relevant data for late effects (esp. carcinogenesis) become available from an analysis of patients treated at ion beam facilities, animal experiments seem to be the only reasonable way to obtain more accurate and systematic data which are needed for a reduction of the uncertainties in the assessment of risks due to galactic cosmic rays in space flight.

Die Relative Biologische Wirksamkeit von Protonen und Ionenstrahlen

Zusammenfassung

Das Verständnis der biologischen Wirksamkeit von Protonen- und Ionenstrahlen ist in zwei sehr unterschiedlichen wissenschaftlichen Bereichen von großer Bedeutung: in der Strahlentherapie und in der Weltraumforschung. Aufgrund der vielen Gemeinsamkeiten der dabei auftretenden Strahlenquelle, liegt die Frage nahe, welche Relevanz die in der Strahlentherapie mit Protonen- und Ionenstrahlen gewonnenen Erfahrungen für die Abschätzung der Risiken aufgrund galaktischer kosmischer Strahlung in der bemannten Raumfahrt haben. Zunächst erfolgt eine Zusammenfassung der wesentlichen Charakteristiken der relativen biologischen Wirksamkeit (RBW) von Protonen- und Ionenstrahlen, wie die Abhängigkeit von Teilchenart, LET und Dosis, sowie den biologischen Systemen und Endpunkten. Die Relevanz dieser Faktoren für die Risikoabschätzung in der Raumfahrt wird dabei hervorgehoben. Das Konzept des klinischen RBW wird dargestellt und die durch in vivo Anwendung gewonnenen Daten werden vorgestellt, wobei der wichtigste Endpunkt für den Strahlenschutz, die Karzinogenese, besonders hervorgehoben wird. Die Datenbasis für die Risikoabschätzung durch galaktische kosmische Strahlung ist fast vollständig auf Tierexperimente begründet, welche an Anlagen zur Ionentherapieanlagen durchgeführt wurden. Insbesondere zur Kazinogenese nach Bestrahlung mit schweren Ionen existieren nur sehr wenige Daten und die Abschätzung von Risikofaktoren ist mit großen Unsicherheiten verbunden. Aus den in der klinischen Anwendung der Ionenstrahlen gewonnenen Daten können daher bisher keine direkten Schlussfolgerungen für die Raumfahrt gezogen werden.

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Angesichts der zu erwartenden größeren Zahl von Patienten welche an den neuen Ionentherapieanlagen behandelt werden, könnte sich dies im nächsten Jahrzehnt ändern. Bis belastbare Daten für Spätreaktionen nach Ionenstrahlung (insbesondere zur Karzinogenese) aus der Nachbeobachtung der Patienten vorliegen, welche mit einer Ionentherapie behandelt wurden, sind Tierexperimente der einzig gangbare Weg um genauere und systematische Daten zu erhalten, welche zur Reduktion der Unsicherheiten in der Abschätzung der Risiken durch galaktische kosmische Strahlung in der Raumfahrt benötigt werden.

Keywords: RBE, protons, heavy ions, radiation therapy

Schlüsselwörter: RBW, Protonen, Schwerionen, Strahlentherapie

Introduction

Biological effects of heavy charged particles on humans play an important role in two very different scientific fields: in radiation therapy with heavy charged particles using protons and heavier ions and in space research for the protection of space travelers from the exposure to galactic cosmic radiation in long-term manned space missions.

Since radiotherapy with protons and ions is of increasing interest worldwide, the knowledge on biological effects due to these particles is increasing. In the last 50 years, more than 50 000 patients have been treated with protons and around 4500 patients with heavy ion beams, respectively [1]. These numbers are much larger than the number of people that have been travelling on board of spaceships, especially, when concerning journeys beyond the earth orbit. The data on the biological effectiveness of proton and ion beams gained in radiotherapy may thus be of value for assessing the radiation risk of space travelers. Moreover, the increasing number of proton and ion beam facilities will strongly increase the available beam-time for ground based research for experimental studies on space radiation protection.

In the following sections, the difference in the radiation fields encountered in radiotherapy and outer space will be outlined, the characteristics of the radiobiological effectiveness of protons and ions will be described and finally some conclusions will be drawn on the influence that the knowledge gained in radiotherapy may have on the assessment of radiation risk in space.

Materials and methods

Sources of protons and ions in outer space and on earth

The knowledge of biological effects from exposure to heavy charged particles is one of the main challenges currently limiting human space flight. The radiation field consist of protons and electrons trapped in the Earth magnetic field, protons and some heavier particles emitted during solar disturbances (known as solar energetic particle events or SEPs) and protons and energetic nuclei of other elements (HZE particles) that constitute galactic cosmic rays (GCR).

For short duration missions in earth orbit, the relevant radiation environment is due to trapped protons and electrons. Since electron fluxes are negligible at energies above 10 MeV, the dose due to electrons is negligible behind the available shielding. Protons are distributed within 4 Earth radii and have energies up to hundreds of MeV. Fluxes of cosmic rays are also present, but are strongly attenuated by the geomagnetic shielding. Typical doses and dose rates in low Earth orbit (LEO) vary as a function of orbit. For the US Shuttle, e.g. average crew dose rates range from 36 μGy/day to 1.1 mGy/day [2].

SEP events are currently not predictable neither in time of their occurrence nor in the maximum flux expected. Protons are their most significant component, with energies up to several hundred MeV. Peak dose rates of 80–90 mGy/day have been measured on board the MIR space station [3], although the total dose of the event of September 29, 1989, integrated over the space station orbit and radiation time, was only 3 mGy. A worst case calculation [4] indicated that for one of the largest observed events in 1989, a total dose to the skin and bone marrow of 1.4 Gy and 0.28 Gy, respectively, can be expected behind 5 g/cm^2 of shielding. The doses and dose rates associated with SEP radiation can thus be life-threatening.

In interplanetary space, GCR fluxes are isotropic and modulated by the solar magnetic field and its cycle. Energies of the GCR particles range from less than a few MeV/u to over 10 GeV/u. Ions from hydrogen up to iron can be found and the LET spectrum can extend to ~1000 keV/μm.