29 MARS 1977

CERN-HS RB 002 PP
C1

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

HS/RB/002/PP

HS DIVISION REPORT

7 March 1977

DETERMINATION OF SOME PARAMETERS
FOR PION RADIOBIOLOGY STUDIES

B. Nordell ^{*)}, J. Baarli, A.H. Sullivan and M. Zielczynski ^{**)}

CERN - Geneva - Switzerland

CM-P00065593

A B S T R A C T

An experimental investigation of the central axis depth-dose and stopping rate distribution of the SIN biomedical pion beam is reported. The pion stopping rate in a thin disc of tissue-equivalent plastic was determined using a counter telescope. The dose rate at the position of this disc "target" was measured using a specially designed parallel-plate tissue-equivalent ionisation chamber. Both dose rate and pion stopping rate are given as a function of depth for beams of two different momenta spread. The energy deposition required per pion stop to fit the measured dose rate curves was calculated and found to be between 37-40 MeV. From the stopping rate measurements the depth-dose distribution of pion interaction dose (star dose) and the dose due to the pion slowing down have been evaluated. The maximum star-dose is found at a depth of about 2 g/cm^2 beyond the maximum of the ionisation dose.

(To be published in "Physics in Biology and Medicine")

^{*)} Pres. address: Inst. of Radiophysics, Stockholm, Sweden
^{**)} Inst. of Nuclear Research, Swierk, Poland

DETERMINATION OF SOME PARAMETERS
FOR PION RADIOBIOLOGY STUDIES

1. Introduction

Beams of negative pions are considered to have properties which make them interesting for application to radiotherapy. Until recently the beams available have been of too low intensity to carry out relevant biological experiments (Raju, Richman 1972). This situation is changing and pion beam intensities are becoming high enough to carry out pre-clinical investigations, of which radiobiological studies form an essential part. The main European contribution in this field will be at the Schweizerisches Institut für Nuklearforschung (SIN) near Zürich, where a high-intensity isochronous cyclotron has been constructed. Among the facilities provided by this machine is a negative pion beam for biomedical applications (Haefeli 1974).

Before biological irradiations can be made with a beam of negative pions it is essential that the beam is studied and the parameters that might influence the radiobiological effects are established. The principal parameters are the absorbed dose-rate in the beam and its variation with depth in tissue-like material. Other factors are also of interest, such as the number of pions stopping per gram. The absorbed dose from a negative pion beam penetrating an absorber is due to slowing down of the pions and absorption of the secondaries from pion nuclear interaction processes (star-dose). A contribution is also due to electron and muon contamination of the beam, decay of the pions into muons, and in-flight nuclear interactions. The principal part of the nuclear interactions take place when the pions come to rest, that is, after they have slowed down through their Bragg ionization peak. As a consequence the maximum pion star-dose is located at a greater depth in the absorber than the maximum total dose. As the predicted biomedical properties of a negative pion beam are associated with the combined effect of dose and high concentration of local energy

deposition that occurs when the pion interacts, the stopping rate distribution of the pions could be the principal parameter influencing the biological effect. The local dose due to pion interactions, the so-called "star-dose", depends on the proportion of the pion rest mass energy (140 MeV) that is deposited locally by the charged nuclear fragments emitted when the pion is captured by an atomic nucleus of the absorber.

2. Setting-up of the beam

The elements of the SIN biomedical beam are shown in fig. 1. The pions are collected from a beryllium target irradiated in the external 590 MeV proton beam and brought down vertically into the biomedical irradiation cave. The beam line is 10.7 m long and is partially evacuated. The mean momentum of the beam, defined by the two bending magnets, was 172 MeV/c. The momentum of the pions in the beam is distributed about this value, and the spread of the momenta could be varied by opening or closing the slit situated between the two bending magnets inside the QSK 72 lens (fig. 1). The beam was focussed with the last lens pair such that the beam profile was circular at the irradiation point, which was chosen to be 1 m above the floor of the irradiation cave (Baarli, Nordell, Sullivan 1976). In order to have maximum dose rate together with a reasonably uniform irradiation of small biological objects, the half-width of the beam was adjusted to be 6 cm (FWHM), which ensured an acceptably uniform dose distribution over a diameter of about 2 cm.

Beam monitoring was made with a thin-walled transmission ionization chamber fitted on the end of the beam pipe 10 cm beyond the last lens, and through which the whole beam passed.

The beam shape was determined in air at five positions along the beam line with X-ray films. The shape of the beam, as it passed through the experimental set-up, is indicated in fig. 2 where the lines are the half-widths (FWHM) of the beam in the X and Y planes. The profiles, as measured with a 1 cm³ spherical tissue-equivalent chamber, are also shown at two selected points along the beam.

3. Dose and stopping rate measurements

All measurements of dose rate and pion stopping rate were made on the beam axis at the irradiation point 1 m above floor level. The dose rate was measured with a specially designed parallel-plate ionization chamber which is shown diagrammatically under the water tank in fig. 2. This chamber has a collector electrode of 25 mm diameter and a single gap of 2 mm. The volume of the chamber was made small enough to be located at a well defined position. The sensitive volume was surrounded by tissue-equivalent material (type Shonka A150) of sufficient thickness that the ionization due to secondaries generated in the plastic could be considered to be in equilibrium in the chamber (95% of the charged particle energy released by pions captured by oxygen or carbon is calculated to be absorbed within a depth of 3 g/cm^2 of water)(Dutrannois, Hamm, Turner, Wright 1972). The chamber was placed inside a polythene phantom of 180 mm diameter (larger than the beam) and 90 mm thick. The chamber was flushed with tissue-equivalent gas at atmospheric pressure: 64.4% CH_4 , 32.4% CO_2 , 3.2% N_2 , where the per cent refers to the partial pressure. This chamber will underestimate the dose from stopped pion interactions by about 1% due to the increase in value of the average energy required to form an ion pair (Turner, Wright, Hamm 1975). The difference in pion interaction products from carbon, which is the major constituent of the chamber, and the oxygen of tissue was expected to result in an overestimation of the dose in the stopped pion peak region by about 8% (Armstrong, Chandler 1974). Due to the uncertainties in extrapolating pion interaction dose from carbon to oxygen, the dose has been determined to the tissue-equivalent material. Any extrapolation to tissue or other biological material is left open. The overall uncertainty in the dose estimations is about 5% (Baarli, Sullivan 1973).

The water tank, located immediately above the ionization chamber (fig. 2), could be filled and emptied remotely and hence the dose rate as a function of depth in water was readily measurable and the results using various momentum slit setting are presented

in fig. 3. The curves are normalized to the beam monitor reading.

The stopping rate of the pions was measured using the counter telescope, shown schematically in fig. 4 (Baarli, Nordell, Sullivan 1976). The stopping rate was determined in a small tissue-equivalent disc of the same diameter and physically in the same position as the sensitive volume of the ionization chamber used for the dose rate measurements.

The telescope consisted of 4 scintillation counters, S_1 , S_2 , S_3 , and S_4 . All scintillators were circular. S_1 ($\emptyset$ 185 mm x 6 mm) was placed above the water absorber and was traversed by the whole beam. S_2 ($\emptyset$ 100 mm x 4 mm) was placed under the water tank and S_3 ($\emptyset$ 25 mm x 1 mm) just above the target which had its centre at the reference point 1 m above the floor. S_4 ($\emptyset$ 50 mm x 4 mm) was placed under the target and could be moved along the beam line relative to the target.

A charged particle stopping in the target is defined by the coincidence S_1, S_2, S_3 , and the anticoincidence $\bar{S}_4$. To allow for particles stopping in S_3 and for particles lost between S_3 and S_4 , due to divergence of the beam, the coincidences $S_1 S_2 S_3 \bar{S}_4$ were measured with and without the target in the beam. This was done by positioning the target remotely into and out of the beam. The difference $S_1 S_2 S_3 \bar{S}_4$ (target in) - $S_1 S_2 S_3 \bar{S}_4$ (target out) was taken as the number of particles stopping in the target.

Stopping rates (in pions per second per g of tissue-equivalent plastic) as a function of depth are shown for momentum slit widths of 24 mm and 65 mm in fig. 5. The slit width of 24 mm corresponds to a momentum spread of 7.8 MeV/c (FWHM) and 65 mm to 13.9 MeV/c (FWHM) (Appel et al. 1976). The muon and electron contamination can be seen beyond the main peak. This contamination has been studied in detail elsewhere (Appel et al. 1976).

The dose contribution from pion interactions can be expected to follow the distribution of the pion stopping rate. In order to determine this separately it was necessary to assign a value defined as "local energy dissipation" per stopped pion and use this to calculate the depth-dose distribution for each pion, backwards from the point where it was known to have stopped. At a depth i the dose D_i is:

$$D_i = S_i \cdot D + \sum_{i}^{\max} \left(\frac{dE}{dx} \right)_k S_{i+k} + D_c$$

where

- S_i = the number of stopped pions at a depth i ,
- D = the "star-dose" or the local energy deposition,
- S_{i+k} = the number of pions stopped at a depth of $i+k$ which hence have a residual range k ,
- $\left(\frac{dE}{dx} \right)_k$ = the stopping power for a pion with a residual range k ,
- D_c = the dose from electrons and muons, assumed to be constant with depth.

The value for D is then varied iteratively until the best fit to the measured depth-dose distribution is obtained. A correction for multiple scattering, resulting in a beam broadening of about 9 mm at the peak depth, was determined from particle flux measured by $S_1 S_2 S_3$ coincidences and stopping pion rate observed by the pion telescope. The dose from contamination, due to muons and electrons, was estimated from the measured total number of muons stopped and the known muon to electron conversion ratio (Appel et al. 1976). The results of the calculations are shown in figs 6 and 7, which indicate the slowing down pion dose, the pion "star-dose", the muon and electron contamination dose, as well as the total dose. The points indicated are the absorbed dose measured with the parallel-plate

ionization chamber. The best fit to the lower momentum spread beam is obtained assuming an "energy deposited locally" from the pion interaction of 37 MeV. The depth distributions of the pion interaction dose for the lower momentum spread has a half-width of 3 cm, which means that the mean energy deposited locally is that deposited within about 1.5 cm from the site of the interaction. This energy deposition corresponds reasonably to that predicted by Monte-Carlo calculations (Dutrannois, Hamm, Turner, Wright 1972). The same fit has been made for the measurement using the larger momentum slit width (65 mm) which requires a value of 40 MeV for the energy deposited per pion interaction. This corresponds with the calculations for the energy deposited within 3g/cm^2 . Discrepancies in the plateau region are thought to be due to the assumption that the energy deposition from in-flight interactions is lost locally, whereas the charged particles produced in this case have a forward momentum, and also because the secondary neutrons are neglected.

4. Discussion

The shape of the stopped pion dose peaks depends on the momentum spread and the divergence of the beam. Not only does dose vary with depth, but also the ratio of "star-dose" to "total dose". For a given total dose it is this ratio that could have an important influence on the biological effectiveness in the beam and hence is a possible parameter for specifying a pion beam for radiobiological irradiations. This ratio of "star-dose" to "total dose" is given as a function of depth in figs 8 and 9 for the two beams studied. This "star-dose" ratio appears to be relatively constant over several g/cm^2 in the peak region of both the large and the small momentum spread beam, but is higher for the beam with the lower momentum spread. The maximum "star-dose" is at a greater depth than the maximum "total dose". For the lower momentum slit width this displacement is about 2 g/cm^2 . The "star-dose" also contributes to the absorbed dose in the plateau region and is estimated to be about 10% of the total dose in this region.

If the "star-dose" is a critical parameter in radiobiological experiments, then maximizing the "star-dose" ratio by reducing the momentum spread in the beam results in a narrow absorbed dose peak and high total dose gradients at the position of the maximum. This, in turn, limits the size of the biological samples that can be reasonably uniformly irradiated. Intercomparisons of radiobiological data from various experiments using stopped negative pions could be made if both "total dose" and per cent "star-dose" values are stated for the particular irradiation conditions to be compared.

We acknowledge the technical assistance of Mr. R.C. Raffnsøe and Mr. S. Larson in these experiments. We also acknowledge the effort of the operating staff of the SIN accelerator to provide the pion beam.

References

- Appel, H. et al., 1976, Atomkernenergie 27, p. 177.
Armstrong, T.W. Chandler, K.C., 1974, ORNL 4462.
Baarli, J., Sullivan, A.H., 1973, Radiology Proc. of XIII Int. Congr. of Radiology, Madrid, pp. 426-431, Publ. Excerpta Medica, Amsterdam
Baarli, J., Nordell, B., Sullivan, A.H., 1976, Atomkernenergie 27, p. 175.
Dutrannois, J., Hamm, R.N., Turner, J.E., Wright, A.H., 1972, Phys. Med. Biol. 17, p. 765.
Haefeli, P., 1974, Fortschr. Röntgenstr. 121 1, p. 101-105.
Raju, M.R., Richman, C., 1972, Current Topics in Rad. Res. Quarterly 8, p. 159-233.
Turner, J.E., Wright, A.H., Hamm, R.N., 1975, Health Physics 29, p. 792.

Figures

1. The SIN biomedical beamline.
2. The variation of the beamline (FWHM) in the X and Y plane as it traverses the experimental apparatus.
3. Depth-dose distribution for various momentum slit settings normalized to the same beam monitor current.
4. Set-up for the pion telescope measurements with scintillation counters S_1 , S_2 , S_3 , and S_4 .
5. Stopping rates of negative pions as a function of water absorber depth measured on the central axis of the beam for momentum slit settings of 24 mm and 65 mm.
6. The curves are calculated from stopping rate measurements and the points are the measured values. Momentum slit 24 mm.
 - a. Pion beam Bragg curve,
 - b. Stopping rate,
 - c. Contamination,
 - d. Total dose.
7. The curves are calculated from stopping rate measurements and the points are the measured values. Momentum slit 65 mm.
 - a. Pion beam Bragg curve,
 - b. Stopping rate,
 - c. Contamination,
 - d. Total dose.
8. Absorbed depth-dose distribution and per cent "star-dose" along the central axis of the stopped pion beam using a water absorber. Momentum slit 24 mm.
9. Absorbed depth-dose distribution and per cent "star-dose" along the central axis of the stopped pion beam using a water absorber. Momentum slit 65 mm.

The π E3 biomedical beam

66040

FIG .1

DOSE MEASUREMENT

FIG. 2

FIG. 3

FIG. 4

FIG. 5

Fig. 6

Fig. 7

FIG. 8

FIG. 9