СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E16-2000-165

V.I.Kostjuchenko[1], A.G.Molokanov, D.F.Nichiporov[1],
F.Spurny[2], B.Vlcek[2]

DOSIMETRIC AND MICRODOSIMETRIC CHARACTERISTICS OF CLINICAL PROTON BEAMS

[1]Institute for Theoretical and Experimental Physics, Moscow, Russia
[2]Department of Radiation Dosimetry, Nuclear Physics Institute,
Czech Academy of Sciences, Prague, Czech Republic

2000

I. INTRODUCTION

A spectrometer of the linear energy transfer (LET) based on the chemically etched polyallyldiglycolcarbonate (PADC) track etched detector (TED) was developed in our laboratory /1-3/ and employed to determine the LET spectra in several radiation beams and fields /4-10/.

This report presents and discusses the dosimetric and microdosimetric characteristics pertinent to the secondary high LET particles born in the detectors irradiated in the proton beams with primary energies of 155 and 200 MeV. The goal of experiments was to study qualitative and quantitative changes in the above characteristics with the depth of the penetrated material.

2. EXPERIMENTAL

2.1. Track Detectors

Polyallyldiglycolcarbonate available from Pershore Moulding, England (curing time 32 hours, thickness 0.5 mm) was used. Each detector was assembled of two sheets of track detectors, with the upper one half-covered with polyethylene (PE). This provides for four different types of «radiators» in front of a detector sheet: no radiator (bare), 2 mm of polyethylene (PE), upper sheet of detector (bare-CR), and upper sheet of detector behind PE (PE-CR).

2.2. Irradiation

Irradiations were performed in the proton clinical beams of the phasotron at the Laboratory of Nuclear Problems of the Joint Institute for Nuclear Research (LNP JINR), Dubna, Russia, and in a clinical beam of the proton synchrotron at the Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia.

The detectors were positioned orthogonally to the beam direction; the proton tissue kerma was about 150 mGy at the beam entrance. To monitor the JINR beam, an ionization chamber was used.

At 155 MeV primary energy, two samples were exposed:

- one with the Lucite degrader 38 mm thick, i.e. with the mean residual energy of about 134 MeV;
- the second one behind additional 100 mm of water as the degrader, i.e. with the mean residual proton energy of about 70 MeV.

At 200 MeV primary energy, three samples were exposed:

- the first one with Lucite degrader 38 mm thick, i.e. with the mean residual proton energy of about 180 MeV;
- the second one, with the additional water degrader 91 mm thick, i.e. with the mean residual proton energy of about 130 MeV; and
- the third one, with the additional water degrader 166 mm thick, i.e. with the mean residual proton energy of about 70 MeV.

The proton beam at ITEP was monitored with a transmission-type current transformer, calibrated with an activation detector based on $^{12}C(p,pn)^{11}C$ reaction.

Two samples were exposed in the ITEP synchrotron beam:

- one at the average residual proton energy of about 190 MeV (degrader thickness 2 g.cm^{-2}).
- the second one, at the average residual proton energy of about 70 MeV (degrader thickness 22.0 g.cm^{-2}).

2.3. LET Spectrometer Based on Chemically Etched PADC TED

After irradiation, each part of the detector assembly was etched in a 5N NaOH at 70°C. Before etching, one corner of each part was irradiated with ^{252}Cf fission fragments, and another one with ^{241}Am alpha particles. This was done to check the exact etching conditions and to determine the bulk etching rate. The etching time was 18 hours, which corresponded to the removal of a layer about 17μm thick on each side of the detector. To determine the LET value of a particle, the etch rate ratio V ($V=V_T/V_B$; where V_B is bulk etching rate and V_T is track etching rate) was primarily established through the determination of track parameters. The track parameters were measured by means of an automatic optical image analyzer LUCIA II based on a Leitz microscope /1-3/. The value of V was calculated by at least two track parameter combinations; the final optimization was performed through the comparison of the removed layer thickness recalculated from V-value and that directly measured through fission fragment track diameters. V-spectra obtained were corrected for the critical angle of the detection and transformed into LET spectra based on the heavy charged particles calibration checked through high dose electron irradiation. The spectrometer allows to determine the LET value of a track between 10 and 700 keV/μm in tissue.

3. RESULTS AND DISCUSSION

3.1. LET spectra

The LET spectrometer allows to study the distributions in two characteristics: the absorbed dose D(L) and the dose equivalent H(L). For H(L)-distributions, quality factors from two recent ICRP Recommendations /11,12/ were used. We observed only minimal differences in the absolute values of differential dosimetric characteristics behind different radiators, as well as in their distributions in LET. Typical examples of the obtained results for 180 MeV protons are presented in Figures 1 and 2. It can be seen that the spectra of both of the differential dose characteristics are quite similar for all four radiators. The same behavior was observed for another group of detectors at all energies for which the full set of radiators was used.

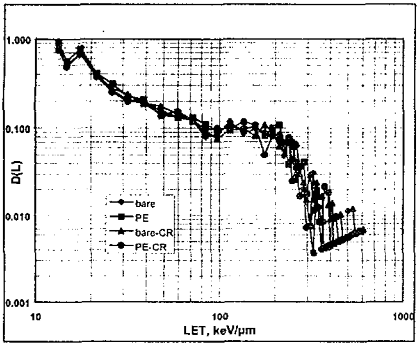


Figure 1: Radiators effect on the D- distribution in LET; E_p =180 MeV

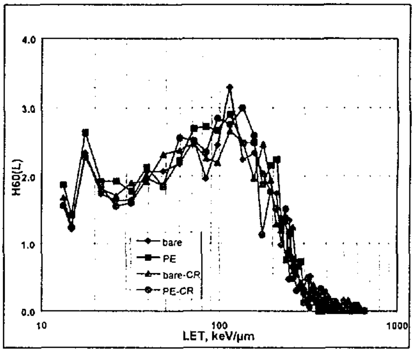


Figure 2: Radiators effect on the H(60)- distribution in LET; E_p =180 MeV

More information on the contribution of different LET particles to the total values can be obtained from the so-called microdosimetric distributions. To illustrate this, the absorbed dose distribution, L*D(L) and the equivalent dose distribution, L*H(L) that are obtained using detector assemblies irradiated with 180 MeV and 134 MeV protons and employing ICRP 60 quality factors, are presented in Figures 3 and 4.

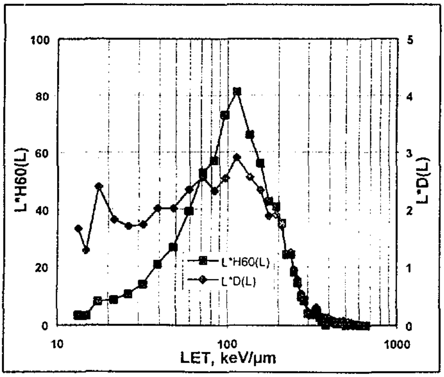


Figure 3: Microdosimetric distributions, set irradiated with 180 MeV protons

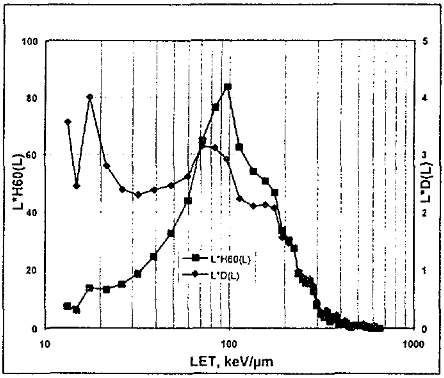


Figure 4: Microdosimetric distributions, set irradiated with 134 MeV protons

One can see that the absorbed dose and the equivalent dose distributions from the two irradiations differ slightly. The assembly irradiated at 134 MeV exhibits relatively higher values of differential quantities, with the spectrum for this assembly shifted to lower LET values. Similar behavior was observed for all other detector assemblies irradiated in all three irradiation runs described in this report. The quantitative differences are presented and discussed in connection with the integral values of dosimetric and microdosimetric characteristics.

3.2. Integral dosimetry and microdosimetry characteristics

Absorbed dose and dose equivalent LET distributions allow one to calculate integral values of the absorbed dose, D and the dose equivalent, H corresponding to the contribution of secondary particles whose tracks are revealed. These integral values are obtained as:

$$D = \int (dN / dL) \cdot L \cdot dL ; \quad (1)$$

$$H = \int (dN / dL) \cdot L \cdot Q(L) \cdot dL ; \quad (2)$$

where dN/dL is the number of tracks in a LET interval, dL;

L is the value of LET;

Q(L) is the quality factor corresponding to the value of L.

The integral values of dosimetric characteristics for the LET range of (12 – 700) keV/μm covered by our spectrometer are presented in Tables 1 - 3. The results show clearly that the contribution of the secondary high LET particles to dose values increases for the same entrance proton energy with depth in tissue-like material .

Table 1: Integral dosimetry values of secondary high LET particles in the beam with primary energy E_p = 155 MeV (Entrance dose 150 mGy, JINR phasotron)

Dosimetric quantity	Unit	Residual E_p, MeV	
		134	70
Absorbed dose	mGy	6.69	28.30
Dose Equivalent (ICRP26)	mSv	48.11	197.9
Dose Equivalent (ICRP60)	mSv	52.61	219.8
Quality factor (ICRP26)		7.19	6.99
Quality factor (ICRP60)		7.86	7.77

Table 2: Integral dosimetric values of secondary high LET particles in the beam with primary energy E_p = 200 MeV (Entrance dose 150 mGy, JINR phasotron)

Dosimetric quantity	Unit	Residual E_p, MeV		
		180	130	70
Absorbed dose	mGy	4.31	7.40	12.70
Dose Equivalent (ICRP26)	mSv	37.80	54.15	98.30
Dose Equivalent (ICRP60)	mSv	43.75	59.98	109.61
Quality factor (ICRP26)		8.77	7.32	7.74
Quality factor (ICRP60)		10.15	8.11	8.63

Table 3: Integral dosimetric values of secondary high LET particles in the beam with primary proton energy E_p =200 MeV (Entrance dose 150 mGy, ITEP synchrotron)

Dosimetric quantity	Unit	Residual E_p, MeV	
		190	70
Absorbed dose	mGy	5.30	18.66
Dose Equivalent (ICRP26)	mSv	44.76	111.77
Dose Equivalent (ICRP60)	mSv	49.59	116.98
Quality factor (ICRP26)		8.45	5.99
Quality factor (ICRP60)		9.36	6.27

As the kinetic energy of the penetrating protons decreases with depth, the dose rate increases. The quantitative data on this increase were taken from our measurements in the JINR beam with a Si-diode, and the examples are presented in Figure 5.

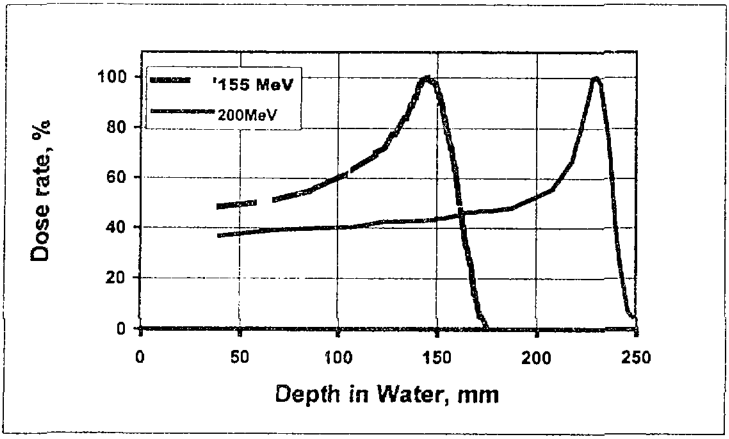


Figure 5: Depth dose distributions of the JINR phasotron proton beams.

Even if the increase in the dose rate is accounted for, the contribution of secondary high LET particles increases along the primary protons` range. The values of the absorbed dose from the high LET secondary particles divided by the absorbed dose of the primary beam at the points of track detectors irradiation are presented in Table 4. It can be seen that these contributions are of the order of a few percent and increase substantially with depth in tissue-like material.

Table 4: Relative contributions of the high LET secondary particles to the absorbed doses

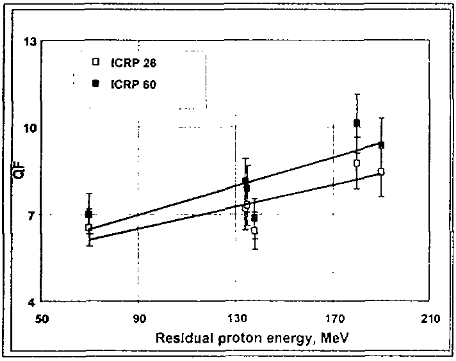
Primary Beam	Residual E_p, MeV	Relative contribution of high LET particles to the absorbed dose, %
155 MeV - JINR	134	4.5[1]
	70	12.9
200 MeV - JINR	180	2.9
	130	4.3
	70	6.2
200 MeV - ITEP	190	3.5
	70	7.8

[1] *Relative standard uncertainty is about ± 15% (2σ) in all cases.*

As regards the values of this contribution at the entrance, these are somewhat higher than the ones reported in our previous studies /5,7,10/, mostly due to improvements in our track parameter determination which has lead to the decrease of the lowest LET value taken into account. To illustrate this phenomenon, when the LET threshold is shifted to 16 keV/μm, the relative contribution decreases to about 60 % of the value given in Table 4 for the 12 keV/μm threshold.

The increase in the relative contribution with depth in tissue-like material can be attributed to the birth of additional secondary particles through the primary proton interactions (lower energy protons and neutrons). Their influence can change not only the relative contribution as a whole, but also its qualitative characteristics, i.e. the LET spectrum of high LET particles read out with our spectrometer. We tried to consider such a possibility through the analysis of the variations in the average values of quality factors corresponding to the detected particle tracks. The trends observed are presented in Figure 6.

Figure 6 indicates that both of the secondary particles` quality factors decrease with depth in tissue-like material, i.e. with decrease in residual proton energy. The decrease is similar for both of the recommended sets of QF values, which suggests that the changes are caused mainly by the increase in contribution of particles with lower LET values. We tried therefore to look at the changes in the relative contribution of particles with LET below 90 keV/μm to the total values of dosimetric characteristics. The results obtained are presented in the Figure 7. One can see that the relative contribution of particles with the LET below 90 keV/μm (which corresponds to the maximum LET value for protons) increases regularly with decrease in residual proton energy, i.e. with depth in tissue-like material.



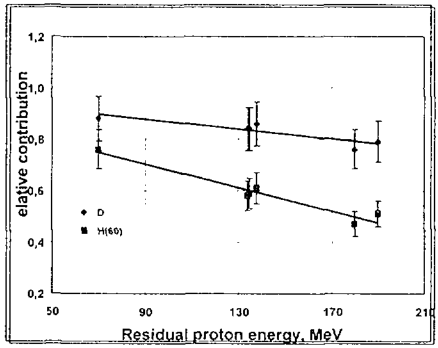


Figure 6: QF(26) and QF(60) as functions of the residual proton energy.

Figure 7: Relative contributions from the particles with LET below 90 keV/μm

4. CONCLUSIONS

There are two aspects that should be discussed in connection with the results presented in this work:

1. The reasons for the increase in the absorbed dose due to high LET secondary particle contribution with depth in tissue-like material observed for few-hundred-MeV protons and the reasons for the qualitative and quantitative variations in this contribution with depth in the material.
2. The importance of this phenomenon for practical applications such as radiotherapy and radiation protection where high energy particles are used.

As was already mentioned, the reasons for the above contribution are the origin of secondary and further generations particles through nuclear interactions and their energy transfer to the matter. The quantitative and qualitative proof to this influence can be obtained through an appropriate particle transport calculation. Efforts are in place in our laboratories to develop this approach to the problem as well.

If ionization losses are taken into account, protons of the energies considered in this work can be regarded as low-LET particles. Our results show, however, that, when all radiation transfer and absorption processes are taken into account, the situation becomes less straightforward.

As regards *radiation protection*, the contribution of secondary high LET charged particles modifies the radiation quality factors. While for ionization losses only the quality factor is about 1.0, for the high LET secondaries it may exceed 10.0 (see Tables 1 through 3). It was calculated that this phenomenon can modify the average QF in a human body by more than a factor of 2 /13/.

As far as *proton radiotherapy* is concerned, the dose due to secondary high LET charged particles changes not only quantitative, but also qualitative characteristics of the beam. While the secondary charged particles contribute only a few percent to the absorbed dose at the beam entrance, the absorbed dose may increase by more than ten percent at greater depths. Besides, due to the increased fraction of high LET particles, radiobiological characteristics of the beam may also change with the depth. This effect may be of a lesser extent than it is assumed through the values of quality factors, but nonetheless it may be responsible for the increased effectiveness of high energy proton radiotherapy /14/.

REFERENCES

1. J. Charvát: «LET spectrometry with polymer track etched detectors.» PhD Thesis, Prague 1986, pp. 1-111
2. F. Spurný, J. Bednář, L. Johansson, A. Sätherberg: «LET spectra of secondary particles in CR39 track etch detectors.» Radiation Measurements 26, (1996), p. 645-649
3. F. Spurný, J. Bednář, K. Turek: «Spectrometry of linear energy transfer with a track etch detectors.» Radiation Measurements 28, (1997), p. 515-518
4. F. Spurný, L. Johansson, A. Sätherberg, J. Bednář, K. Turek: «Contribution of Secondary Heavy Particles to the Absorbed Dose from High Energy Photon Beams.» Phys. Med. Biol. 41, (1996), p. 2643-2656
5. V. E. Dudkin, F. Spurný: «Contribution of Secondary High LET particles to the Energy Transfer from High Energy Protons.» Proc. IRPA9 Congress, Vienna 1996, vol. 2., p. 250-253
6. F. Spurný, J. Bednář, K. Turek, V. P. Bamblevski: «Spectrometry of the LET in High Energy Reference Fields.» Bezp. jaderné energie 5(43), (1997), p. 354-358
7. F. Spurný, J. Bednář, K. Turek, J.-F. Bottollier-Depois, V. E. Dudkin: «Secondary Particles Contribution to the Dose Characteristics in High Energy Particle Beams and Fields.» Radiation Measurements 28, (1997), p. 505-513
8. J.-F. Bottollier-Depois, F. Spurný, L. Plawinski, I. Votočková, J. Bednář, M. Viso and A. Labarthe: «Dosimetry during the First IBIS Facility Flight.» Adv. Space Research 22, (1998), p. 517-520
9. F. Spurný, V.P. Bamblevski, B. Vlček: « Spectra of the Linear Energy Transfer Measured with a Track Etch Spectrometer in the Beam of 1 GeV Protons; The Contribution of Secondary Particles to the Dose »; Report DRD NPI AS CR 455/98, Prague, November 1998

10. A.G. Molokanov, F. Spurný, B. Vlček: «The Contribution of Secondary Heavy Charged Particles to Dosimetric Quantities of Radiotherapy Proton Beams Using a Track Etch LET Spectrometer.»; JINR Communication E16-99-98, Dubna, 1999
11. «Recommendations of the International Commission on Radiological Protection". ICRP Publication 26, Annals of ICRP, 1, No. 3, (1977)
12. «Recommendations of the International Commission on Radiological Protection". ICRP Publication 60, Annals of ICRP, 21, No. 1-3, (1990)
13. V.E. Dudkin et al. Health Physics 1971
14. A. Wambersie and H.G. Menzel: «Dose Specification in Heavy Particle Therapy (A Review)»; Radiat. Prot. Dosim. 70, (1997), p.517-527

Received by Publishing Department
on July 18, 2000.