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COMPARISON OF NEUTRON THERAPY BEAMS PRODUCED BY 50 MeV DEUTERONS AND 65 MeV PROTONS ON BERYLLIUM

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Neutron therapy has been performed routinely, since March 1978, at the cyclotron Cyclone of Louvain-la-Neuve with d(50)-Be neutron beams. The use of the deuterons bombarding a beryllium target appeared to be the easiest way to obtain high neutron fluxes, and in fact at all the cyclotrons used at that time for therapeutic applications this type of reaction was adopted. The maximum available deuteron energy from the cyclotron (50 MeV) was selected, mainly in order to obtain as good dose distributions as possible.

In a second stage, the use of neutron beams produced by bombarding a beryllium target with protons has been considered. First of all, neutron beams, produced at proton energies as high as 65 MeV could significantly improve the dose distributions of the treatments. Secondly, in the prospect of initiating proton beam therapy (at Cyclone protons up to about 90 MeV are available) the use of neutron beams produced by the same particles would be more practical if neutron therapy and proton therapy patients are treated on the same day. Thirdly, the possibility of a 'time sharing procedure' is contemplated between therapy and isotope production, in which use of protons is certainly more suitable.

However production of neutrons from the p→Be reaction implies some disadvantages. Higher beam currents are needed if the dose rate should be maintained, resulting in higher energy dissipation in the beryllium target. Moreover, higher activation levels are to be expected which is a disadvantage from a health physics point of view. Nevertheless, a reasonable solution to these problems could be found and the first treatments with p(65)-Be neutrons were started in December 1981. The energy of 65 MeV was chosen for reasons of cyclotron reliability. A routine use of the p(65)-Be neutron beam for clinical application was started in March 1982.

Before the clinical application, the biologic characteristics of the neutron beams produced by protons on beryllium have been investigated. In particular it was checked that increasing the incident particle energy would not raise OER and hence would not reduce part of the expected benefit. In fact the same OER value was found for d(50)-Be and p(75)-Be neutron beams for mammalian cell survival (GUICHARD et coll. 1980) and Vicia Faba (VAN DAM & WAMBERSIE 1981) growth delay. As far as RBE is concerned, a reduction of about 10 per cent was observed for different systems, when using p(75)-Be as compared with d(50)-Be neutron beams. Under these conditions, the therapeutic benefit of the introduction of p(65)-Be neutrons is directly related to the improved dose distributions; the same irradiation plans can generally be maintained and only a small adjustment of the delivered dose has to be made in order to take into account the change in depth dose and RBE.

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Materials and Methods

The cyclotron

The neutron therapy facility at Louvain-la-Neuve has been described by WAMBERSIE et coll. (1978, 1979).

A vertical neutron beam was adopted, because it appeared to be the best fixed beam for positioning the majority of the patients. Up to now, neutrons were produced by bombarding a 10 mm thick beryllium target with 50 MeV deuterons. This beryllium target is mounted in a 7 mm thick brass support, cooled with water. The collimation system consists of a fixed iron shield and a series of interchangeable inserts. These inserts, 80 cm long, are made of a mixture of epoxy, iron and boron, the availaible field sizes range from 6 cm×8 cm up to 16 cm×20 cm at a target-skin distance (SSD) of 157 cm. These inserts were focussed on the 3 cm in diameter focal spot. The field sizes, used in this text, are nominal field sizes: the real field sizes (50% isodose position or light beam) are in general 5 per cent larger at this SSD.

Production of p(65)-Be beams

In principle p(65)-Be neutron beams can be produced in the same installation; however to improve the p(65)-Be beam quality some modifications have to be performed (BEWLEY et coll. 1980). Neutron spectra produced by protons on beryllium differ in shape from those produced by deuterons; the former typically having 2 regions: a high energy region, extending almost to the energy of the incident protons and an intense low energy component (AMOLS et coll. 1977).

A filtration with a hydrogenous material, such as polythene, is recommended to attenuate this low energy component. In Table 1 the depth of the 50 per cent isodose and the corresponding dose rates for different filter thicknesses are shown for a 16 cm×20 cm field. As can be seen the choice of the adequate filter is a compromise between an increase in depth dose and a reduction of the dose rate. At Louvain-la-Neuve a 2 cm thick polythene filter was selected.

Table 1

Depth of the 50 per cent isodose and dose rate for p(65)-Be neutron beams (16 cm×20 cm field) as a function of the polythene filter thickness. The dose rate without filter is taken as reference

Filter thickness (cm)	Fifty per cent isodose depth (cm H_2O)	Relative dose rate
0 (no filter)	18.1	1
2	18.8	0.87
5	19.2	0.74

Production of neutron beams from protons on beryllium raises some activation problems. It has been observed, after several treatments with p(65)-Be neutrons that the activation in the treatment room is raised by a factor of 2 (up to 0.2 $mSv \cdot h^{-1}$) as compared with the activation levels after d(50)-Be treatments. Moreover, and in the beam itself, a significant increase of dose rate from activation was observed (up to 10–20 $mSv \cdot h^{-1}$ at the patient skin position, depending on total treatment time) measurements indicated that this was mainly due to activation, by protons, of the brass in the target support. A mechanical system with 2 target positions was therefore constructed so that the irradiated target is automatically removed from the beam line after the treatment. In these conditions, the dose rate in the beam resulting from activation is reduced down to 0.2 $mSv \cdot h^{-1}$ and the dose rate in the treatment room is reduced by a factor of about 2.

Dosimetric techniques in d(50)-Be and p(65)-Be neutron beams

Total absorbed dose measurements. Measurements were carried out in a phantom with 2 tissue equivalent chambers (T.E.): a 0.1 cm^3 cylindric T.E. ionization chamber manufactured by Far West Technology (FWT, EG & G, Goleta, USA) and a T.E. parallel plate ionization chamber. For relative measurements all chambers were filled with air; it has been controlled that the air/T.E.-gas ratio remains practically constant at all depths (OCTAVE-PRIGNOT et coll. 1980). The photon calibration as well as the determination of the total absorbed dose were made following the ECNEU protocol (BROERSE et coll. 1981) and were recently compared with those of the Rijswijk and Amsterdam group (OCTAVE-PRIGNOT et coll. 1982). The phantom, 50 cm×50 cm×50 cm in size, is filled with water or with a T.E. liquid, composed following ICRU recommendations (ICRU No. 26, 1977). The density of this liquid was measured to be 1.12. The displacement corrections for these chambers were calculat-

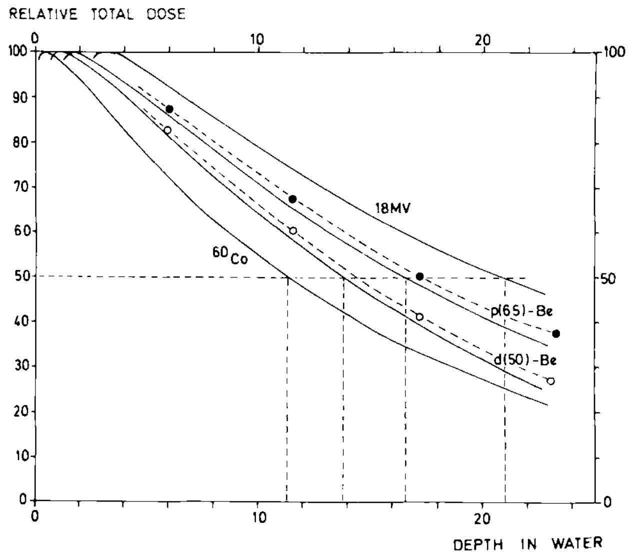

Fig. 1. Depth dose curves for different beam qualities for a 10 cm×10 cm field. The neutron depth doses were measured in water (—) and T.E. liquid (---). The measurements in T.E. liquid were corrected to unit density. SSD: 100 cm, 157 cm, 157 cm and 80 cm for 18 MV photons, p(65)-Be neutrons (2 cm thick polythene filter), d(50)-Be neutrons and ^{60}Co photons, respectively. For clarity, build-up curves are not shown. Relative total dose in per cent and depth in water in cm.

ed following the measurements of ZOETELIEF et coll. (1981).

Build up curves were measured with a special constructed parallel plate ionization chamber in a polystyrene phantom with dimensions 30 cm×30 cm×30 cm, used for daily dosimetry.

Determination of the gamma component. The gamma component was determined according to the classical two-detector method (ICRU No. 26). It was derived from measurements with a Geiger-Müller counter (ZP 1311) surrounded by a ^{6}LiF cap. The relative neutron sensitivity (k_U) of this counter was determined following the method already described (PIHET et coll. 1981), k_U values of 0.061 and 0.041 were estimated for p(65)-Be and d(50)-Be, respectively.

For the d(50)-Be neutron beam, the gamma contribution to the total absorbed dose (D_G/D_G+D_N) increases from 1.6 to 4.1 per cent when going from 1.5 to 20 cm depth in water for a 10 cm×10 cm field. Preliminary results with the p(65)-Be neutron beam indicate a rather strong increase of the gamma component. At a depth of 1.8 cm (maximum of the depth dose curve) a value of 6.4 per cent was obtained for a 6 cm×8 cm field whereas for the d(50)-Be beam this was only 0.8 per cent for the same field and at 1.2 cm depth (maximum of the depth dose curve).

Results and Discussion

Dose rates. The change from deuterons to protons on beryllium decrease significantly the dose rate. In the actual configuration (10 mm beryllium+2 cm polythene filter) a dose rate of 0.015 $Gy \cdot min^{-1} \cdot \mu A^{-1}$ at build up position in a phantom is obtained for a 10 cm×10 cm field at SSD 157 cm. This would result in a dose rate of about 0.22 $Gy \cdot min^{-1}$ for a beam current, routinely adjusted to 15 μA. As a comparison for the d(50)-Be neutrons a dose rate of 0.10 $Gy \cdot min^{-1} \cdot \mu A^{-1}$ for the same field and the same SSD was obtained. Routinely the beam current for the 50 MeV deuterons was adjusted, allowing for a dose rate of 0.50 $Gy \cdot min^{-1}$ but, if necessary, dose rates up to 1 $Gy \cdot min^{-1}$ could be achieved. AWSCHALOM et coll. (1980) reported that for protons on beryllium a significant increase of the dose rate can be obtained by increasing the beryllium target thickness. For this reason a second target will be mounted in the new target system, allowing the application of 2 targets with different thicknesses, and, if necessary supported by holders made of brass or carbon. This also resolves the activation problems.

Depth dose. In Fig. 1 the depth dose ($D_{n+\gamma}$) curves for a 10 cm×10 cm field are compared for the d(50)-Be and the p(65)-Be neutron beams, measured in water and in T.E. liquid. The depth dose curves measured in T.E. liquid are corrected to unit density by multiplying each depth d by the density 1.12 and adjusting the dose at the point by an inverse square law $(SSD+d)^2/(SSD+1.12\ d)^2$. As can be seen, if corrected to unit density, both neutron beams have a slightly greater penetration in the T.E. liquid, as expected from the higher hydrogen concentration in water. For instance, at the depth of the 50 per cent isodose in water, a 2 per cent higher dose or a 4 per cent deeper penetration is found in the T.E. liquid for both neutron fields. Comparable results were found for other field sizes. In the same figure the depth dose curves for ^{60}Co and 18 MV photons from a linear accelerator are indicated. Neutron depth dose data for all fields appear in Tables 2 and 3.

Variation of the 50 per cent isodose depths in water is shown in Fig. 2 as a function of the equivalent square field side. This side is obtained for rectangular fields by the formula $L_{eq}=2\ LH/(L+H)$. This empirical formula, currently used for photons, is obviously still valid for these neutrons.

Table 2

Output factors and percentage depth dose data ($D_{n+\gamma}$) in water for d(50)-Be neutron fields at SSD 157 cm

Depth (cm)	Collimator (cm) and output factor (in parentheses)						
	6×8 (0.953)	8×10 (0.988)	10×10 (1.000)	10×12 (1.006)	10×16 (1.023)	13×16 (1.036)	16×20 (1.060)
1.2	100	100	100	100	100	100	100
3	92.8	93.5	93.8	94.2	94.5	95.0	95.4
4	87.8	89.1	89.7	90.1	90.5	91.0	91.6
5	82.7	84.4	85.3	85.5	86.1	86.8	87.6
6	77.8	79.6	80.7	80.9	81.7	82.7	83.5
7	72.9	74.9	76.1	76.5	77.3	78.6	79.5
8	68.1	70.3	71.7	72.2	73.1	74.6	75.6
9	63.4	65.9	67.4	68.0	68.9	70.6	71.9
10	58.9	61.7	63.2	64.0	64.9	66.7	68.3
12	50.5	53.9	55.2	56.2	57.3	59.2	61.3
14	43.1	46.6	48.0	49.0	50.3	52.2	54.6
16	36.6	39.9	41.6	42.5	44.0	45.8	48.3
18	31.2	33.9	35.8	36.6	38.2	40.2	42.4
20	26.6	29.1	30.6	31.5	33.1	35.1	37.2

Table 3

Output factors and percentage depth dose data ($D_{n+\gamma}$) in water for p(65)-Be neutron fields at SSD 157 cm

Depth (cm)	Collimator (cm) and output factor (in parentheses)						
	6×8 (0.935)	8×10 (0.976)	10×10 (1.000)	10×12 (1.010)	10×16 (1.034)	13×16 (1.060)	16×20 (1.088)
1.8	100	100	100	100	100	100	100
3	96.5	96.8	96.8	96.7	97.1	97.2	97.3
4	93.0	93.3	93.3	93.7	94.3	94.4	94.5
5	88.8	89.4	89.5	90.1	91.2	91.3	91.8
6	84.4	85.4	85.6	86.3	87.2	87.3	88.7
7	80.2	81.7	81.8	82.9	83.5	84.2	85.4
8	76.1	78.0	78.0	79.1	79.7	80.3	82.0
9	72.2	74.2	74.3	75.4	76.1	76.9	78.6
10	68.5	70.6	70.7	71.6	72.6	73.6	75.1
12	60.9	63.5	64.0	64.7	65.8	67.1	68.7
14	54.2	57.0	57.5	58.5	59.7	60.9	62.7
16	48.3	51.0	51.7	52.7	54.1	55.3	57.2
18	42.9	45.6	46.4	47.4	48.9	50.2	52.0
20	38.2	40.8	41.5	42.8	44.2	45.6	47.5

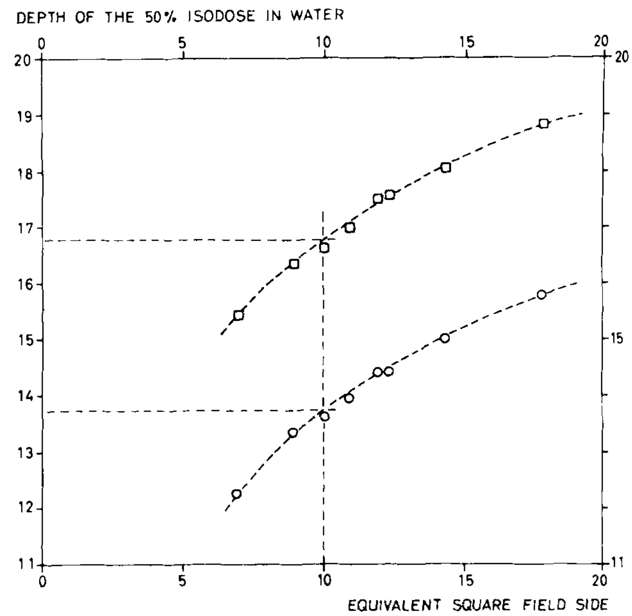

Fig. 2. Depth (cm) of the 50 per cent isodose in water for the p(65)-Be (□, 2 cm thick polythene filter) and d(50)-Be (○) neutron beams as a function of the equivalent square field side (cm).

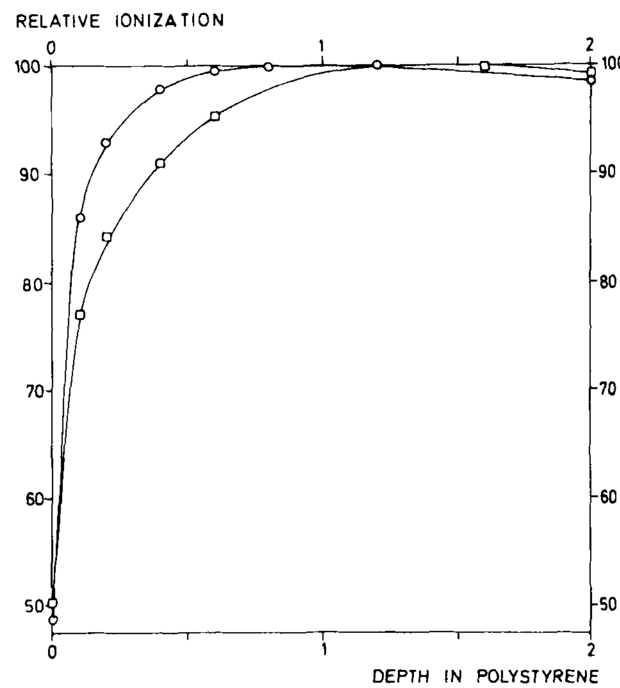

Fig. 3. Relative ionization (per cent) as a function of depth (cm) in the first centimeters of a polystyrene phantom irradiated with d(50)-Be (○) and p(65)-Be (□) neutron beams for a 10 cm×10 cm field. The collimator—skin distance was 20 cm.

The 50 per cent isodose in water for p(65)-Be neutrons lies, for all fields, approximately 3 cm deeper than for d(50)-Be neutrons.

Build up. Fig. 3 shows the build up curves measured in polystyrene for both neutron fields. At both energies there is a broad maximum: between 0.8 cm and 1.2 cm for d(50)-Be and 1.2 cm and 1.8 cm for p(65)-Be. The dose at the surface is nearly the same for both energies: 49 per cent for d(50)-Be and 51

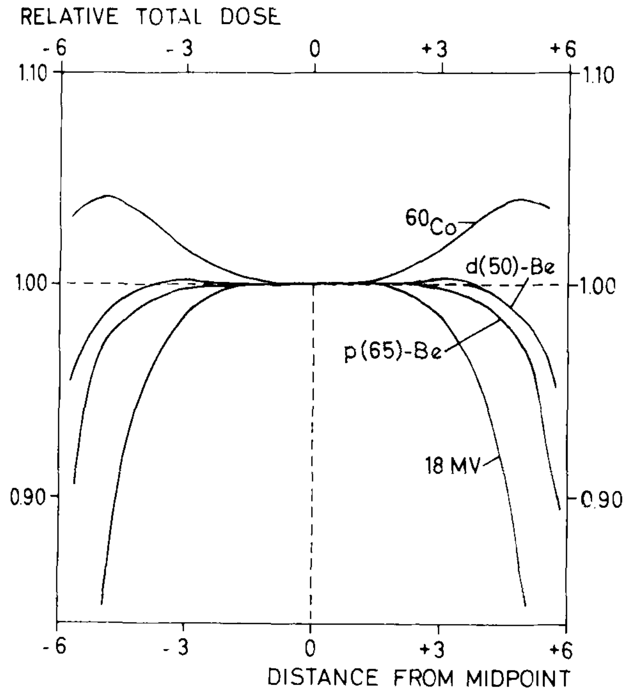

Fig. 4. Total dose variation along the central axis of two parallel opposed 10 cm×10 cm fields for a patient thickness of 12 cm. Four different beam qualities are presented (cf. Fig. 1). Distance from midpoint in cm.

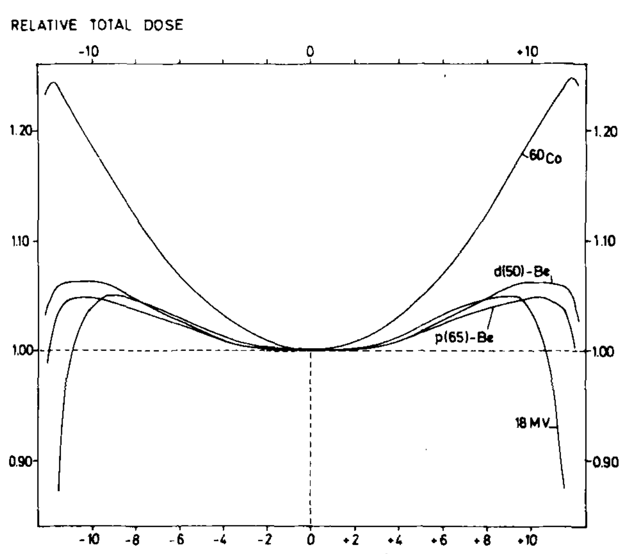

Fig. 5. Total dose variation along the central axis of two parallel opposed 16 cm×20 cm fields for a patient thickness of 25 cm. Four different beam qualities are presented (cf. Fig. 1). Distance from midpoint in cm.

per cent for p(65)-Be; the slightly higher percentage for p(65)-Be could possibly be due to a higher content of charged particles in the p(65)-Be neutron beam. Shielding with 2 mm lead at the end of the collimator reduces these values to 40 and 41 per cent for d(50)-Be and p(65)-Be, respectively.

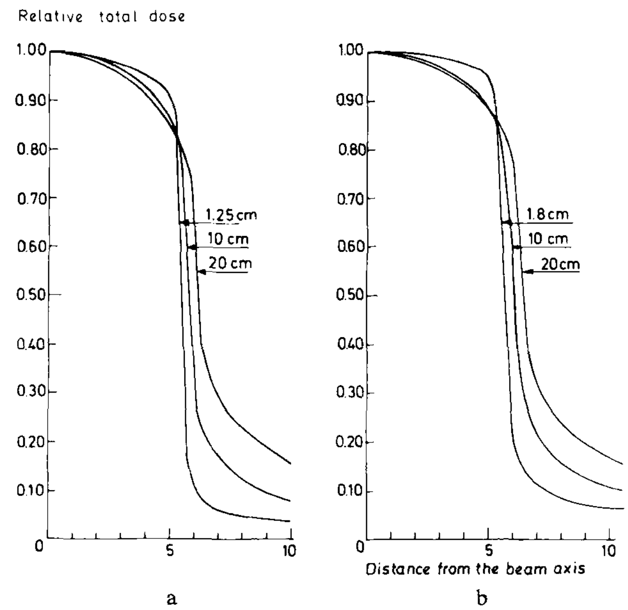

Fig. 6. Total absorbed dose ($D_n+\gamma$). Profiles for both neutron beams with a 10 cm×10 cm field at different depths in a water phantom. SSD 157 cm. a) d(50)-Be neutrons. b) p(65)-Be neutrons. Distance from beam axis in cm.

Opposed field arrangement. In Figs 4 and 5 the dose distributions along the central axis are presented for 2 opposed fields. The differences in dose distributions in depth are small between both neutron energies and the 18 MV photon field. The gain obtained with p(65)-Be versus d(50)-Be neutrons is mainly due to an increase in skin sparing.

Transverse absorbed dose distribution. In Fig. 6 the profiles are compared for the p(65)-Be and d(50)-Be neutron beams at different depths for the 10 cm×10 cm field. The lateral distance between the 80 and 20 per cent isodose curve is currently chosen as a criterion in order to evaluate the efficiency of the collimation system. At the depth of the maximum dose, a lateral distance of 0.7 cm was found for p(65)-Be and 0.5 cm for d(50)-Be, rising to 1.7 cm and 1.3 cm, respectively, at 10 cm depth. This indicates that the same collimation system is still efficient for a proton on beryllium beam of higher energy.

Isodose distribution. An isodose distribution for both energies can be generated by combining the transverse dose and the depth dose data. Fig. 7 shows the computer generated isodose distributions for both energies obtained by a matrix representation (VYNCKIER et coll. 1981). These isodose distributions were computed by combining central depth dose data and transverse dose data measured at the depths of maximum dose, 7 cm, 10 cm, 15 cm and 20

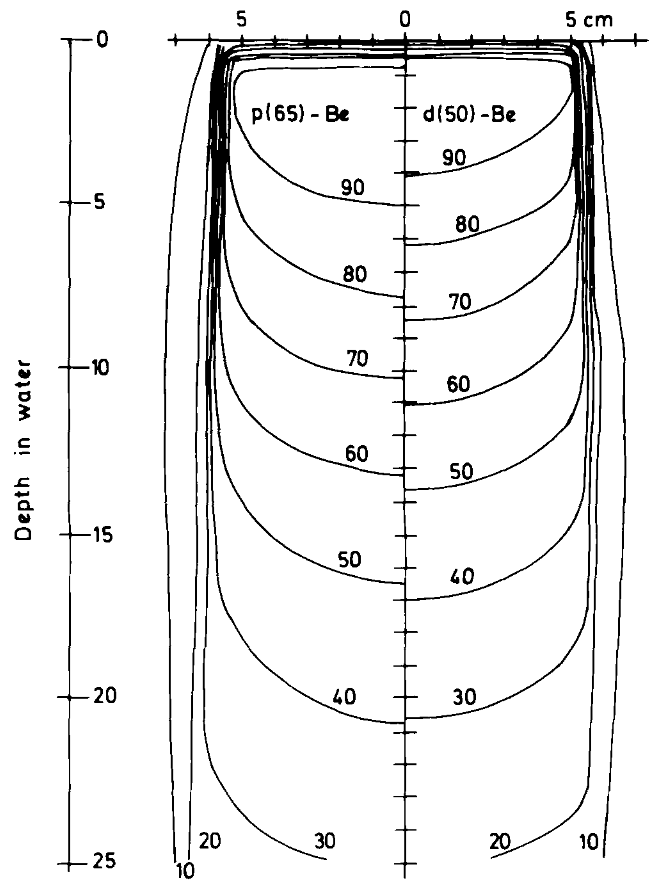

Fig. 7. Computed isodose curves for single p(65)-Be and d(50)-Be neutron beams ($D_n+\gamma$ dose distribution). The matrix was constructed using the depth dose data along the central axis and 5 profile curves at the depths of maximum dose, 7, 10, 15 and 20 cm H_2O. SSD 157 cm. Field size 10 cm×10 cm. Depth in water in cm.

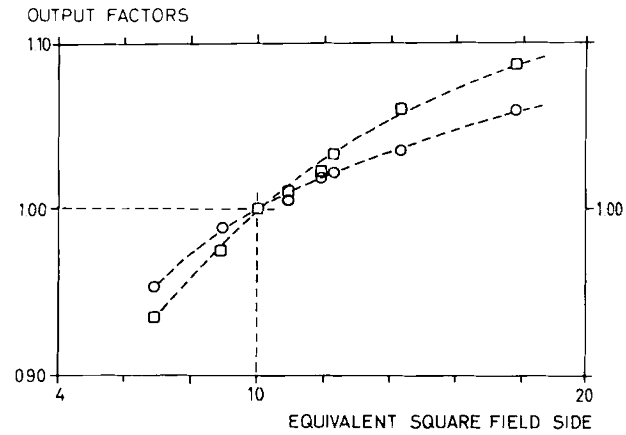

Fig. 8. Output factors normalized to a 10 cm side square field as a function of the equivalent square field side (cm). The output factors were measured in a polystyrene phantom at 1.2 and 1.8 cm depth for d(50)-Be (○) and p(65)-Be (□) neutrons, respectively (i.e. maxium build-up depth). SSD 157 cm.

cm in H_2O. The better penetration and the less sharper penumbra for the p(65)-Be neutron beam can be observed.

Output factors for both neutron beams are compared in Fig. 8. These output factors are normalized to the 10 cm×10 cm field output. They were measured in a polystyrene phantom at build up position (1.2 cm for d(50)-Be and 1.8 cm for p(65)-Be) using the integrated beam current as monitor. The same factors were found if a transmission ionization chamber located 25 cm beneath the target was used as second monitor. The formula, 2 LH/(L+H) can be used to normalize the output of the rectangular fields. Variation of the output factors are larger for the p(65)-Be neutron beams than for the d(50)-Be neutron beams.

Conclusion

Neutron beams, produced by 50 MeV deuterons and routinely used since 1978 for therapeutic applications are being replaced by neutron beams produced by 65 MeV protons.

A p(65)-Be neutron beam was produced without any major modification of the installation; a 2 cm thick polythene filter has been added in order to eliminate the lower component of the neutron spectrum. A thicker beryllium target will currently be used with the protons in order to improve the dose rate. A mechanical system was constructed, allowing the use of these 2 targets and automatically removing the irradiated target from the beam line in order to reduce the exposure to the personnel.

For the p(65)-Be neutrons an improved depth dose curve was obtained (0.6 cm deeper dose maximum and 3 cm deeper penetration of the 50% isodose level) and an only slightly changed profile curve, showing that the collimation system is still efficient for these higher energy neutrons (distance of axis between the 80% and 20% isodose increased only from 0.5 cm to 0.7 cm). A rather strong increase of the gamma component was obtained.

Since OER values were similar and the RBE differed only about 10 per cent between the 2 beam qualities, the expected therapeutic gain could be evaluated from the comparison of the respective dose distributions. This gain was mainly manifested by a better skin sparing.

SUMMARY

Neutron beams produced by bombarding a 10 cm thick beryllium target with 50 MeV deuterons have been used at Louvain-la-Neuve since nearly 4 years for routine thera-

peutic applications. At the end of 1981 they were replaced by neutron beams produced by 65 MeV protons on beryllium, mainly in order to improve the beam penetration in tissues. However, production of neutrons from the p→Be reaction implies some disadvantages, mainly a lower dose rate and a higher activation level. In order to solve the problem a new target configuration was designed, consisting of a remote handled system which permits the use of 2 different target assemblies. The irradiated target is automatically removed immediately after the irradiation which greatly protects against exposure to the staff. The dosimetric characteristics of the d(50)-Be and p(65)-Be neutron beams are compared.

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