HOSPITAL BASED SUPERCONDUCTING CYCLOTRON FOR NEUTRON THERAPY: MEDICAL PHYSICS PERSPECTIVE

M. Yudelev, J. Burmeister, Karmanos Cancer Institute, Wayne State University, Detroit, MI 48201.

E. Blosser, MedCyc Corporation, East Lansing, MI.

R. L. Maughan, C. Kota, University of Pennsylvania, Philadelphia, PA.

Abstract

The neutron therapy facility at the Gershenson Radiation Oncology Center, Harper University Hospital in Detroit has been operational since September 1991. The d(48.5)+Be beam is produced in a gantry mounted superconducting cyclotron designed and built at the National Superconducting Cyclotron Laboratory (NSCL). Measurements were performed in order to obtain the physical characteristics of the neutron beam and to collect the data necessary for treatment planning. This included profiles of the dose distribution in a water phantom, relative output factors and the design of various beam modifiers, i.e. wedges and tissue compensators. The beam was calibrated in accordance with international protocol for fast neutron dosimetry. Dosimetry and radiobiology intercomparisons with three neutron therapy facilities were performed prior to clinical use. The radiation safety program was established in order to monitor and reduce the exposure levels of the personnel. The activation products were identified and the exposure in the treatment room was mapped. A comprehensive quality assurance (QA) program was developed to sustain safe and reliable operation of the unit at treatment standards comparable to those for conventional photon radiation. The program can be divided into three major parts: maintenance of the cyclotron and related hardware; QA of the neutron beam dosimetry and treatment delivery; safety and radiation protection. In addition the neutron beam is used in various non-clinical applications. Among these are the microdosimetric characterization of the beam, the effects of tissue heterogeneity on dose distribution, the development of boron neutron capture enhanced fast neutron therapy and variety of radiobiology experiments.

1 INTRODUCTION

The Detroit neutron therapy facility is a product of collaboration between National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University and Gershenson Radiation Oncology Center at Harper Hospital. It is the first application of a compact superconducting cyclotron to fast neutron radiation therapy [1]. The past clinical experience of neutron therapy as well as physical and economic factors were considered in setting forth the requirements and design specification of the cyclotron and the facility [2]. The detailed description of the neutron therapy facility and the beam physical characteristics were presented elsewhere [3]. In this work the contribution of medical physics to the operation of neutron therapy facility at Harper Hospital during its 10 years of operation is presented.

2 ACCEPTANCE AND COMMISSIONING OF THE NEUTRON BEAM

2.1 Initial Acceptance Testing

Series of tests were performed to ensure that the beam characteristics are in compliance with the specifications and requirements for external beam radiation therapy [4]. The location of mechanical and the radiation isocenters were defined for the gantry and the collimator rotations. The light field produced by the beam light localizer [5] was aligned to coincide with the Half Width at Full Maximum (HWFM) of the radiation beam profile for a range of field sizes and distances.

2.2 Beam Flattening Filter

The forward peaking nature of neutrons produced by glancing incidence of deuterons on the Be target required addition of a flattening filter to achieve the desired beam flatness and symmetry. The flattening filter was produced by stacking thirteen 1.45 mm thick stainless steel leaves attenuating the neutron beam by 2.7% each. The shape and the position of each leaf relative to each other corresponded to the isodose lines measured in a plane perpendicular to beam central axis at the isocenter in 2.7% increments. The actual size of the leaves was obtained by scaling back to the plane of the filter position upstream. The final filter design was modified later in several iterations based on the measurements of beam profiles at a variety of field sizes and depths in the phantom. The resulting beam flatness is less than 9% and 3% measured at 1 cm and 10 cm depths, respectively, in the 25×25 cm^2 field. The beam symmetry is better than 1.3% measured at 1.2 cm depth in the 5×5 cm^2 field.

2.3 Beam Physical Characteristics.

Depth-dose characteristics of the beam are approximately equivalent to those of a 4 MV photon beam, and the skin sparing and penumbra characteristics of the beam are slightly better than of a ^{60}Co beam. The depth at which 50% of the maximum dose is attainable for

10×10 cm^2 field size is 13.6 cm. The surface dose for a 10×10 cm^2 field is approximately 42% and the depth at which the maximum dose occurs (d_{max}) in tissue equivalent plastic is 0.9 cm. The maximum on target beam current is limited to 15 µA in order to prevent overheating of the target, and the maximum dose rate attained at d_{max} and at an SSD of 182.9 cm in a 10 cm x 10 cm field is 48 cGy min. The normal operating condition of 12.5 µA gives a dose rate of 40 cGy per min.

The useful clinical neutron beam is produced by a multirod collimator consisting of 84 rows of tungsten rods arranged in "close-packed" two opposed arrays [6]. The rods are pushed by Styrofoam templates cut into the required shape, thus producing an opening between two rod arrays. The solid tungsten equivalent thickness of all the 84 rods arrays is 216.3 cm. The maximum transmission through the multirod collimator is approximately 4% and < 2% at off axis points. At a depth of 1.2 cm in a water phantom the penumbra width, defined as the distance between the 80% and 20% isodose lines, is 0.55 cm measured along an axis parallel to the direction of the rods and 0.65 mm along the axis perpendicular to the rods. At a depth of 10 cm in the water phantom the distance between the 20% and 80% isodose lines is further degraded to 1.75 cm and 1.95 cm in the directions parallel and perpendicular to the rods, respectively.

Some of the physical parameters of the neutron beam are listed in Table 1.

Table 1. Neutron beam characteristics.

Source-to-axis distance	182.9 cm
Dose rate	48 cGy per min for 15 µA on target (Max).
Depth dose	50% at 13.6 cm depth for a 10 x 10 cm^2 field
Depth of max. dose	9 mm of Tissue Equivalent Plastic
Surface dose	42% of d_{max}
Collimator	Multirod type
Field size	0 x 0 to 26.5 x 30 cm^2
Penumbra (20 - 80%)	− 0.6 cm at d_{max} − 1.9 cm at 10 cm depth

2.4 Wedge Filters

Three polyethylene wedges rotating the 50% isodose line by 15^0, 30^0 and 45^0 respectively are available as accessories to the collimator. The "wedged" isodose distribution can also be achieved by arranging the tungsten rods in such a way as to gradually attenuate the beam. This attenuation of the beam by the tungsten rods can be used to create partially blocked areas.

3 BEAM DATA FOR TREATMNET PLANNING

The treatment planning system is capable to perform 3D dose calculation and supports conformal treatment planning for photon as well as for neutron external beam therapy [7]. The dose calculation algorithm utilises Cunningham's scatter model [8]. The dose calculations are performed in terms of total (neutron + gamma) dose, and correction to account for tissue heterogeneities may be applied.

To adopt and test the scatter model for neutron beam calculations a set of central axis and lateral profiles as well as peak scatter factors were measured for a number of rectangular and irregularly shaped fields. These data were used to calculate the Tissue- and Scatter-to-Air Ratios (TAR and SAR) as well as to determine the other beam parameters pertinent to the treatment planning algorithm and to evaluate its accuracy in clinical cases. The agreement between the measured data and the data derived from the treatment planning program is usually within 2% for the central axis points and about 5% for the lateral beam profiles [9].

4 NEUTRON BEAM CALIBRATION

The neutron beam monitor ionization chambers were calibrated in accordance with the recommendations of International Commission on Radiological Units and Measurements (ICRU) [10].

A neutron dosimetry intercomparison with three neutron therapy centers was performed in d(48.5)+Be neutron beam at Harper Hospital [11]. The doses were measured independently by each participant in water phantom at depths of 6, 10 and 15 cm. The results of the intercomparison are shown in table 2 and demonstrate an agreement better than 1.0% all participants of the intercomparison.

Table 2. Dose in cGy per 100 monitor units measured at three depths in water

Depth	6 cm	10 cm	15 cm
Mean±Std. Dev.	87.8±0.7	68.2±0.5	48.0±0.3

5 QUALITY ASSURANCE PROCEDURES.

The quality assurance program (QA) was designed to be uniform with the QA program for other teletherapy machines in the institution and is based on recommendations of the American Association of Physicists in Medicine Task Group 40 [12]. The program is divided into three major groups: (1) maintenance of the cyclotron and related hardware; (2) QA of the neutron beam dosimetry and treatment delivery; and (3) safety and radiation protection.

5.1 Cyclotron Facility Maintenance

The periodic maintenance of the cyclotron and liquid helium production systems is performed by technical personnel. These procedures include cleaning of the ion sources, replacement of the source cathode and the radiofrequency coupler. The oil and turbomechanical pumps of the vacuum system are checked, greased and replaced periodically. The tests of the interlock safety system are performed daily.

5.2 Neutron Beam QA

The tests of neutron beam dosimetry and treatment delivery are performed on a daily, monthly and annual basis. They include the beam output constancy, the monitor system calibration, the field flatness and symmetry, the beam alignment with optical devices, the mechanical and radiation isocentricity, the patient set-up aids, as well as treatment port verification system. The calibration of the monitor system is adjusted if the output exceeds ±2% of preset value.

5.3 Radiation Safety

The sources of the induced activity from the d(48.5)+Be fast neutron beam were investigated. The activation spectra were measured at different locations in the treatment vault. Peaks corresponding to ^{28}Al, ^{56}Mn, ^{24}Na, ^{64}Cu, ^{66}Cu, and ^{187}W were present in the spectra.

The dose equivalents due to the build-up of induced activation were measured at six locations in the room. The highest levels were registered around the treatment head [13]. The distribution of exposure rates in the treatment room is shown in Table 3.

Table 3. Exposure rate (mRem/hr) in the treatment room during a typical day of cyclotron operation.

Time	Couch	Isocenter	Collimator
a.m.	2.2	3.7	17.8
p.m.	12.7	48	22.0

The radiation exposure to the staff involved in the operation of the neutron therapy unit is monitored by personnel dosimeters on a daily and monthly basis.

A radiation survey was performed in order to confirm the shielding design and to assure the safety of the personnel involved in the operation of the unit [14]. The radiation levels around the neutron therapy vault are monitored on a monthly basis and comply with the recommendations of the National Council on Radiation Protection and Measurements (NCRP) and State of Michigan regulations.

6 DOSIMETRY OF NON-CLINICAL APPLICATIONS

6.1 Mixed Beam Dosimetry

The measurements of separate neutron and gamma dose components in the beam were done using the "twin detector" technique employing Tissue Equivalent (TE) ionization chamber and miniature Geiger-Muller (GM) counter with relative neutron sensitivity of 0.025 [15]. For 10×10 cm^2 beam the gamma component is 2.9% at depth 2.5 cm and gradually increases to 11.4% at 30 cm depth. The gamma component increases with distance from the edge of the field and reaches 29%, 42% and 59% at depths of 5, 10 and 20 cm, respectively, at distance of 30 cm from the central axis.

6.2 Effects of Tissue Heterogeneity

The effect of heterogeneity on neutron dose distribution was measured and compared with calculations for lung, bone and adipose tissue substitutes. It was found that tissue heterogeneity corrections employed in the treatment planning algorithm may be applied for neutron calculations if the density and tissue kerma effects are taken into account.

6.3 Microdosimetric Spectra

Experimental microdosimetry has been instituted as part of the neutron therapy physics research program. Microdosimetric data measured in the neutron therapy beam provides independent validation for dosimetry data and accurate separation of photon and neutron components within the beam [16]. It is also quite useful for assessment of beam quality and estimation of the relative biological effectiveness of fast neutron therapy. Novel investigations into small-volume detector design, tissue-equivalent plastics, and the therapeutic potentials of boron neutron capture therapy as a boost to fast neutron therapy are among the outgrowths of microdosimetry research at Harper Hospital. Microdosimetric spectra were measured with tissue-equivalent and 10B-loaded tissue-equivalent proportional counters [17]. This dual proportional counter technique provides the complete secondary charged particle energy spectra for the photon and neutron absorbed dose components as well as a direct measure of the absorbed dose resulting from the boron neutron capture reaction.

REFERENCES

[1] H. G. Blosser, J. Dekamp, J. Griffin, D. Johnson, F. Marti, B. Milton, J. Vincent, G. Blosser, E. Jamison, R. Maughan, W. Powers, J. Purcell and W. Young, "Compact superconducting cyclotrons for neutron therapy," IEEE Trans. Nuc.. Sci. **NS32** 3287-3291 (1985).

[2] R. L. Maughan, W. E. Powers and H. G. Blosser, "A superconducting cyclotron for neutron therapy," Medical Physics **21:** 779-785 (1994).

[3] R. L. Maughan and M. Yudelev, "Physical characteristics of a clinical d(48.5)+Be neutron therapy beam produced by a superconducting cyclotron," Medical Physics **22:** 1459-1465 (1995).

[4] AAPM Report No.13, "Physical aspects of Quality Assurance in Radiation Therapy." (New York: American Institute of Physics), 1986.

[5] R. L. Maughan., "A light localizer for use at large distances from a radiation source", Medical Physics **25**: 892-893, 1998.

[6] R. L. Maughan, G. F. Blosser, E. B. Blosser, M. Yudelev, J. D. Forman, H. G. Blosser, and W. E. Powers. "Maltirod collimator for neutron therapy." Int. J. Radiation Oncology Biol. Phys. **34**: 411-420, (1996).

[7] T. He, D. P. Ragan, and C. F. Mesina, "Clinical Experience in 3D CT Simulation and Treatment Planning." Medical Physics **21**: 928, (1994).

[8] H. E. Jones and J. R. Cunningham, Physics of Radiology. 4th edn. (Springfield, IL: Charles C. Thomas) (1983).

[9] M. Yudelev, R.L. Maughan, T. He and D. P. Ragan, "Evaluation of the dose algorithm based on the scatter model applied for neutron therapy treatment planning." Radiation Protection dosimetry **70**: 513-516, (1997).

[10] ICRU Report #45, "Clinical neutron dosimetry part I: Determination of absorbed dose in patient treated by external beam of fast neutrons." International Commission on Radiation Units and Measurements, Bethesda, MD, (1989).

[11] R. L. Maughan, M. Yudelev, S. D. Brossard, J. L. Horton, and S. Vynckier. "An international neutron dosimetry intercomparison." Medical Physics **22**: 2103-2104, (1995)

[12] G. J. Kutcher, L. Coia, M. Gillin, W. F. Hanson, S. Leibel, R. J. Morton, J. R. Palta, J. A. Purdy, L. E. Reinstein, G. K. Svensson, M. Weller, L. Wingfield. "Comprehensive QA for radiation oncology: report of AAPM Radiation Therapy Committee Task Group 40." Medical Physics 21: 581-618, (1994).

[13] M. Yudelev, R.L. Maughan, L. B. Jordan, R, Saxena. "Dose equivalents to neutron therapy facility staff due to induced activation." Health Physics **72**: 361-367, (1997).

[14] M. Yudelev, R. L. Maughan, K. Dunlap. "Shielding and radiation safety around a superconducting cyclotron neutron therapy facility." Health Physics **69**: 130-136, (1995).

[15] R. L. Maughan, M. Yudelev, C. Kota. "A measurements of the fast-neutron sensitivity of a Geiger-Muller detector in the pulsed neutron beam from a

[15] R. L. Maughan, M. Yudelev, C. Kota. "A measurements of the fast-neutron sensitivity of a Geiger-Muller detector in the pulsed neutron beam from aconducting cyclotron". Phys. Med. Biol. **41**: 1341-1351, (1996).

[16] C. Kota, R. L. Maughan "Microdosimetric specification of the radiation quality of a d(48.5)+Be fast neutron beam produced by a superconducting cyclotron" Medical Physics **23**: 1591-1599, (1996).

[17] J. Burmeister, C. Kota, R. L. Maughan and A. J. Waker "Miniature tissue-equivalent proportional counters for BNCT and BNCEFNT dosimetry" Medical Physics **28**: 1911-25, (2001).