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Neutron Measurements for Intensity Modulated Radiation Therapy

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***Abstract* – The beam-on time for intensity modulated radiation therapy (IMRT) is increased significantly compared with conventional radiotherapy treatments. Further, the presence of beam modulation devices may potentially affect neutron production. Therefore, neutron measurements were performed for 15 MV photon beams on a Varian Clinac accelerator to determine the impact of IMRT on neutron dose equivalent to the patient.**

***Key words* – IMRT, MLC, neutron, dose**

I. INTRODUCTION

A few papers have been published on measurements and calculations of neutron production for high-energy photon beams from medical accelerators (Bourgois 1997, Liu 1997, Kase 1998). However, no neutron measurements have been reported for intensity modulated radiation therapy (IMRT). Typically the number of monitor units (M.U.) used in IMRT is about 2 to 4 times higher than the total M.U. for conventional treatments. In addition multi-leaf collimator (MLC) leaves are opened and closed during IMRT, affecting the neutron production and scattering. This paper reports the results of measurements and discusses the impact of IMRT on the neutron dose to the patient.

II. Experiment

Measurements were performed at Stanford Hospital with a Clinac 2300C/D medical accelerator operating in the 15 MV photon mode. Neutron measurements were performed with moderated gold foils, Neutrak-144[3] CR-39 track etch detectors (incorporated in the Luxel[3] dosimeter)and the BD PND[4] bubble detectors. Photon measurements were made with the aluminium oxide optically stimulated luminescent dosimeter (OSLD) contained in the Luxel dosimeter. The detectors were placed at different locations ranging from 0 to 100 cm from the isocenter (located at 1 m from the target) on the couch surface. The source-to-couch-surface distance was set at 100 cm and the couch angle at 180^0. Measurements were performed under the following onditions:

a) Field size 20 cm x 20 cm defined by jaws with MLC leaves fully open
b) Field size 20 cm x 20 cm defined by jaws with MLC leaves closed
c) Field size 0 cm x 0 cm (i.e. jaws closed)
d) An IMRT treatment

At least 2 detectors (of the same type) were used per irradiation condition.

The gold foils were 0.025 mm thick. The moderator was made of a cylinder of low-density polyethylene (diameter = 15.87cm, length = 15.66 cm), covered with a boron shield which absorbs the themal neutrons. The moderated gold foils measure the fast neutron fluence, which can be converted to dose equivalent by means of appropriate conversion factors (NCRP 79). The moderated foils have a response nearly independent of energy in the range of 3 to 14 MeV. The foils were calibrated with a Pu-Be neutron source. Activated foils were counted in a pancake Geiger Mueller counter.

The Neutrak-144 dosimeter was calibrated with an Am-Be neutron source. It detects neutrons over an energy range of 40 keV to 35 MeV. After irradiation the dosimeters were processed by the manufacturer.

The BD-PND dosimeters are temperature compensated bubble detectors. They were calibrated with an Am-Be neutron source and detect neutrons over an energy range of 100 keV to 14 MeV. Bubble detectors with two different sensitivities (~ 10 bubbles/μSv and 60 bubbles/μSv)were used. According to the manufacturer the sensitivity is accurate to within ± 20% over the temperature range of 20 to 37 ^{0} C. The bubbles were counted directly by eye and from the projection on to a TV screen (Ipe 1987a).

According to the manufacturer, the aluminum oxide OSLD has a minimum detectable energy of 5 keV and a precision of ± 1 mrem.

III Results and Discussion

a) Neutron Dose Equivalent

Figures 1, 2 and 3 show the neutron dose equivalent (normalized to one M.U.) along the patient plane as measured by the moderated gold foils, Neutrak-144 and the BD PND detectors, respectively. Error bars are not shown on the figures because in most cases they are smaller in size than the markers in the legend. The range of statistical errors ($\pm1\sigma$) observed for the gold foils, Neutrak-144 and BD-PND dosimeters were 2 to 9%, 0.5 to 17% and 2 to30%, respectively.

As expected, in all cases the neutron dose equivalent inside the beam is greater than the neutron dose equivalent outside the beam. The highest neutron dose equivalent is observed for the first condition (field size = 20 cm x 20 cm, leaves open). When the leaves are closed the dose equivalent at

the isocenter decreases by about a factor of 2.0, 1.8 and 2.4 for the gold foils, Neutrak-144, and BD-PND dosimeters respectively. When the jaws are closed (but the leaves are open), the corresponding factors are 3.5, 3.0 and 4.2, respectively. The jaws are about 1.9 cm thicker than the leaves. The decrease can be explained in the following manner.The jaws and leaves are made of tungsten and provide significant attenuation of photons. If the dosimeter is susceptible to photon induced effects, the closing of the leaves will result in a decrease in any photon-induced responses. Although some neutron production may occur in the jaws and the leaves, they also cause the neutrons to undergo elastic, inelastic and (n, 2n) reactions. The net result is a reduction in neutron dose equivalent because of a) neutrons scattered out of the primary beam and b) reduction in neutron energy due to inelastic reactions which softens the neutron spectrum.
It is interesting to note that the dose equivalent at the isocenter for IMRT is lower than the condition with the leaves closed. The IMRT treatment consists of 9 different fields. The field sizes are fairly small with a maximum field size of 7.4 cm x 8.4 cm.

These results indicate that neutron production from IMRT inside the beam is lower than from conventional treatment represented by the open field (field size = 20 cm x 20 cm, leaves open) . The neutron dose equivalent (cSv/M.U.) at the isocenter is about 0.0012 for this particular IMRT as compared to 0.03 for a 20 cm x 20 cm open field (figures 1and 2). The total M.U. for this IMRT case is 755 M.U. as compared to about 200 M.U. for a typical conventional treatment. Thus the total neutron dose equivalent at the isocenter for this IMRT is comparable to that for a 20 cm x 20 cm open field even though the beam-on time has increased by a factor of 3.8.

In general the neutron dose outside the beam decreases with distance from the isocenter and the diffeneces between the various conditions is less pronounced. It appears that the closing of the leaves and jaws does not have a significant impact on the neutron doses at these distances.The highest neutron dose equivalent (cSv/M.U.) for IMRT outside the treatment field is 0.0008 (fig.2) at 20 cm as compared to 0.0014 for the open field. Thus tissues outside the treatment field can receive a neutron dose equivalent of. 0.6 cSv for IMRT as compared to 0.3 cSv for the open field. Thus the l neutron dose equivalent for IMRT (755 MU) at 20 cm is 2 times higher because of the increased beam-on time. The neutron dose equivalent is not significant from a therapy point of view.

Table 1 provides a comparison of neutron dose equivalents from this work with published values for afield size of 0 cm x 0 cm at 15 MV. The calculated values are within about 50%and 20% of the measured values inside and outside the field, respectively.

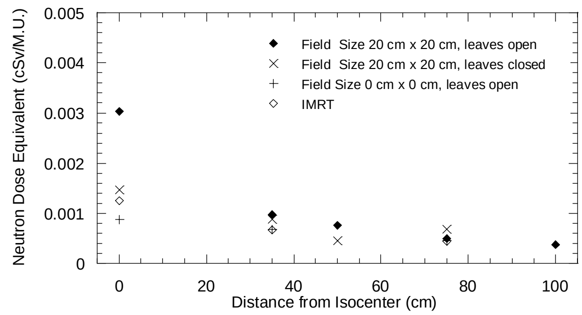

Fig. 1: Neutron dose equivalent (gold foil) at different locations along the patient plane.

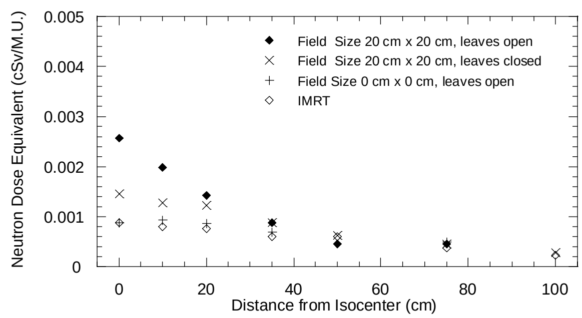

Fig. 2: Neutron dose equivalent (Neutrak-144) at different locations along the patient plane

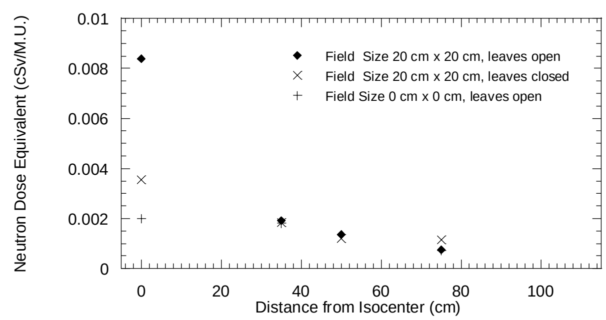

Fig. 3: Neutron dose equivalent (BD-PND) at different locations along the patient plane

Reference	Neutron Fluence (cm^{-2}/cGy)		Detector Or Calculations
	Inside Field	Outside Field	
This work	5.5×10^6	4.7×10^6 (35 cm)	Gold
Kase1998	8.4×10^6	3.7×10^6 (40 cm)	Calculations

Table 1: Comparison of measurements with published calculations

Fig. 4 shows a comparison of the neutron dose equivalents as measured by the various dosimeters along the patient plane for a field size of 20 cm x 20 cm.

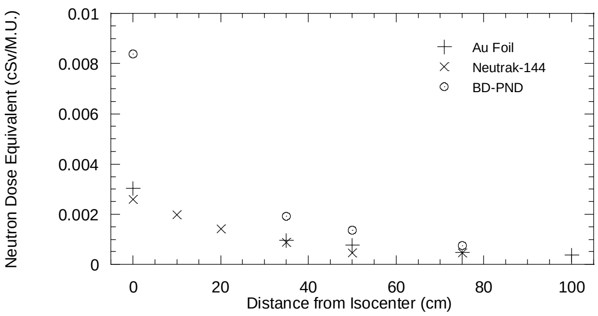

Fig 4: Comparison of neutron dose equivalents measured by different dosimeters

There is reasonable agreement between the gold foil and Neutrak-144 data. The slight differences can probably be attributed to the different energy responses of the two dosimeters. The BD-PND dosimeter overresponds by about a factor of 3 inside the beam, due to photon-induced reactions (Ipe 1987a). The Neutrak-144 is also susceptible to photon-induced reactions but the effect is much smaller (Ipe 1987b). McCall (McCall 1976) has shown that photon-induced effects at 15 MeV in the boron-lined moderator is negligible. Since the actual constituents of the dosimeters are not known, it is not possible to list all possible reactions. Some probable reactions are:

$^{2}D(\gamma,n)p$ (threshold energy =2.22 MeV)
$^{16}O(\gamma,\alpha)^{12}C$ (threshold energy = 7.2 MeV)
$^{12}C(\gamma,\alpha)^{8}Be \rightarrow 2\alpha$ (threshold energy = 7.4 MeV)

The BD PND dosimeter responses outside the treatment field are just slightly higher than the gold foil and Neutrak-144 responses.

b) Photon Dose

Fig 5 shows the photon dose as measured by the aluminium oxide, at different locations along the patient plane. The statistical errors ($\pm 1\sigma$) for the dosimeters varied between 2 and 16%.

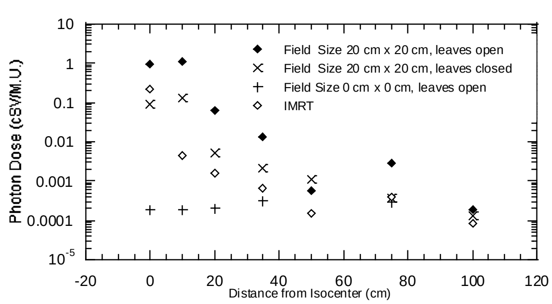

Fig. 5: Photon Dose (Aluminium Oxide) at different locations along the patient plane

As expected, the highest doses are observed for the field size of 20 cm x 20 cm. At the isocenter, the doses drop by about a factor of 5000, when the jaws are closed, whereas, the attenuation provided by closing the leaves is only about a factor of 10. Since there is a small gap between the leaves when they are closed , there is some leakage of photons which may partially explain the low attenuation factor.

The photon dose (cSv/M.U.) from IMRT at the isocenter is about 0.22 compared to about 1 for a 20 cm x 20 cm open field. For an IMRT treatment of 755 M.U. the photon dose approaches that for the open field , as expected.
The photon dose (cSv/M.U.) from IMRT at 35 cm is 0.0006 compared to 0.014 for a 20 cm x 20 cm open field. For an IMRT treatment of 755 M.U. the total photon dose at 35 cm is about 6 times smaller than the dose for the open field (200 M.U.)

Future work will involve a complete Monte-Carlo simulation of the accelerator head and the surrounding room geometry in order to determine:

a) the neutron yield from the various components – target, primary collimators, jaws, MLC-leaves, etc.
b) the integral neutron fluence, energy spectra, and dose equivalent along the patient plane
c) the responses of the various detectors to neutrons after folding in the energy –response curves of the detectors
d) the photon-induced responses of the various detectors.

V. Conclusions

Neutron measurements were performed for a 15 MV photon beam from a Varian Clinac accelerator to determine the impact of IMRT on neutron dose equivalent to the patient. The use of MLCs does not increase neutron production. For an IMRT treatment of 755 M.U., the neutron dose equivalent at the isocenter is comparable to the dose equivalent for a 20 cm x 20 cm open field. Neutron doses outside the treatment field increase by a factor of about 2 for IMRT, primarily because of the increased beam-on time.
Bubble detectors should not be used to assess neutron dose inside the treatment field because of increased response from photon-induced reactions in the dosimeter.

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