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# Innovative utilization of compact disc for measuring fast neutron generated from a 10 MV medical linear accelerator

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**ABSTRACT**

**Background**: High-energy photons produced from a medical linear accelerator (LINAC) have long been used as one of the most effective ways for treating cancers. During the treatment process, some photo neutrons are unavoidably created by [γ,n] reactions, imposing additional and undesirable dose on a patient. This amount of unplanned dose from photo neutrons can potentially harm the patient as well as medical personnel during the treatment.

**Objectives**: To develop a methodology for measuring fast neutron dose generated from 10 MV LINAC by employing polycarbonate from base material of compact disk (CDs) and a fast neutron converter.

**Materials and methods**: The polycarbonate base layer of CDs has been applied to fast neutron dosimetry with nuclear track method by combining with polymethyl methacrylate (PMMA) converter for fast neutrons. A number of CDs badges were irradiated with high energy photon from 10 MV Elekta Synergy LINAC in the solid water phantom at depth of 0, 2.5, 5, 10, 15 and 20 cm then etched with potassium hydroxide ethanol water (PEW) solution that containing with potassium hydroxide, ethanol and water with ratio of 15:45:40. The optimal condition for the chemical etching were found at 60±2 °C, for 14 hr.

**Results**: Comparison of neutron equivalent doses from measurement of CD track detector and CR-39 track detector has shown that the maximum fast neutron dose equivalent was at depth of 5 cm of phantom. This agreement has confirmed that the CD track detector can be employed to measure fast neutron doses produced from LINAC in an accurate and affordable fashion.

**Conclusion**: It is confirmed that the CD track detector can be employed to measure fast neutron doses produced from LINAC in an accurate and affordable fashion.

## Introduction

Medical linear accelerator (LINAC) is widely considered as one of many standards for cancer treatment. LINAC relies on producing high-energy photon and electron radiations and delivering them to targets. However, photon with energy higher than 8 MeV may activate the target materials by a (γ,n) reaction. Examples of such materials are $^{56}Fe$, $^{184}W$ and $^{208}Pb$. These produced photo-neutrons contaminate the LINAC beams and potentially become a cause of second cancer due to high linear energy transfer (LET) which allows photo neutrons to penetrate through medium and to indirectly generate free ions increasing cancer risks.[1-3] Cheol-Soo Park et al. also observed additional radiation dose from fast and thermal photo neutrons generated from a 10 MV LINAC using CR-39 method. It was found that neutron generation increased when a wedge filter was used.[4]

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However, there is no evidence that excessive dose from contaminating photo neutrons is taken into consideration during the radiation treatment planning. It is partly because of complex nature of neutron interactions, suitable neutron dosimeter and radiation measurements for high-energy and fast neutrons.

There were various methods used to measure photo neutron dose generated during radiation treatment with LINAC.[5] Hassan Ali Nedaie et al. used thermo-luminescent dosimeter (TLD) to measure neutron generated from Varian and Elekta LINAC and compared TLD600 and TLD700 measurements with MCNP calculations. The comparison showed that TLD600 and TLD700 were not suitable dosimeters for neutron dosimetry inside LINAC due to extremely high photon flux. They concluded that MCNP was more suitable.[6] MCNP, Monte Carlo N-Particle Transport Code System, is a three-dimension computational transport code that can be used practically for all particles and all energies with all reactions given in a particular cross-section evaluation such as ENDF/B-VI. Applications for the code are quite broad, including neutron dosimetry. MCNP5 development has begun in 1994 as a code merger of MCNP4B[7] and LAHET 2.8[8] and constantly been developed. In addition, the most common neutron measurement method is using neutron detectors, $BF_3$ or $^3$He gas-filled proportional counter, $^6$Li glass scintillator. Most of neutron detectors are only applicable in the thermal region. However, they are made possible for fast neutron detection by incorporating hydrogenous materials in Bonner sphere systems. Activation foil has an advantage that it is transparent to radiation in the treatment field. However, using activation foil comes with an expense for a need of a gamma spectrometry system which is usually not available on site. Solid-state nuclear track detectors (SSNTDs) are a passive method for neutron measurement, which can register charged particles by the neutron-induced damage caused along their interaction path. SSNTDs in the market are called differently, depending on their types and manufacturers. Their backbone materials are made of a variation of plastic polymers such as Cellulose nitrate, Allyl diglycol carbonate, Diethylene glycol bis (allyl carbonate) and Polycarbonate.[9] These plastic polymers are electrical insulators that can readily register ion tracks. However, neutrons cannot leave ion tracks on these plastic polymers as they are neutral particles. The plastic polymers must then be doped with converters before being used as a neutron detector. One of the most common SSNTDs is CR-39 detector due to its ability to measure both thermal and fast neutrons with appropriate neutron converter and chemical etching method. CR-39 detector is responsive to a wide range of neutron energy while it is insensitive to gamma, beta, ultraviolet (UV) and x-ray. In addition, neutron tracks produced in CR-39 detector are easily assessed by a microscope.[9] A need to import CR-39 detector makes it less economical for domestic use. Makrofol-polycarbonate has been a frequently used base material for neutron detectors.[10, 11] and that Makrofol and equivalent polycarbonates are widely used as a basic structural material for compact discs (CDs). An attempt to reprocess used CDs as SSTNDs would make neutron dose assessment more readily available and more economical.

This study was aimed to develop a methodology (or technique) for measuring fast neutron dose generated from 10 MV LINAC, which is the most common model of medical LINACs in THAILAND, by using polycarbonate from base material of CDs and a particle converter. Equivalent doses obtained from the prototype are compared with results from CR-39 neutron detector for evaluating the accuracy and applicability of this technique in the actual cancer treatment and planning.

## Materials and methods

### Preparation of CDs fast neutron track detector (CDs detector)

The new CDs (Princo, CD-R 700MB 56X) were used in this study. CDs were scraped out of lacquer, acrylic and metal layers and were left with only a polycarbonate layer. CDs were cut into rectangular badges with 2-cm wide and 7-cm long. The rectangular pieces are smeared with neutron converter composing of boron powder. Boron can capture thermal neutrons and release alpha particles through $^{10}B(n,\alpha)^7Li$ reactions and polymethyl methacrylate or acrylic (PMMA), a hydrogenous material, can convert fast neutrons into recoil proton by elastic scattering. Each badge is segmented into four regions with different material modification. The first region is the original CD material without any modification. The second region only has aluminium tape applied on its surface. The first two regions are designed to control regions for this study. The third region has boron converter attached to its surface by aluminium tape. The fourth region has PMMA converter attached to its surface. Cadmium sheet is applied across all regions to make sure that only fast neutrons interact with the badge. This experimental setup is demonstrated in Figure 1.

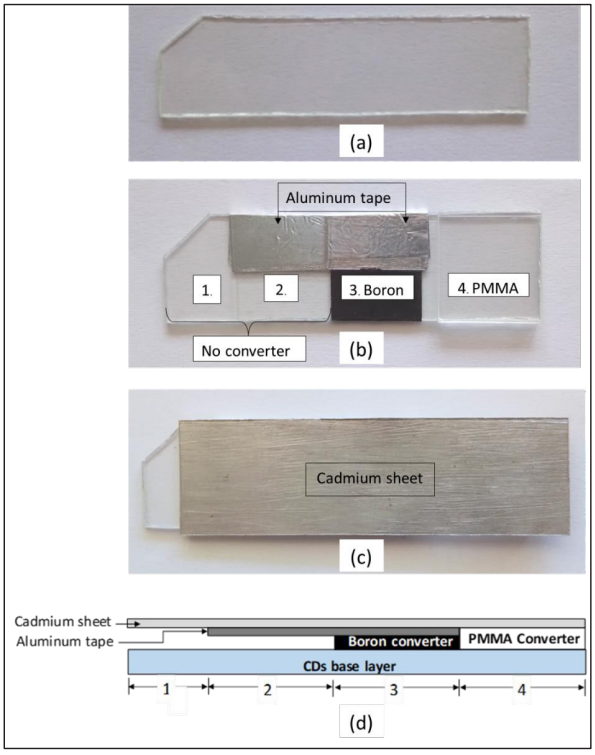


***Figure 1****. CDs track detector composed of first layer of a: CDs base (polycarbonate), b: second layer of various neutron convertor, c: covered with cadmium sheet, and d: side view illustrating diagram of CDs track detector.*

**Irradiation**

The 10 MV Elekta Synergy LINAC (Elekta AB, Stockholm, Sweden) at Lampang Cancer Hospital was used to irradiate a number of CDs badges. The irradiating conditions were set on the LINAC to deliver an irradiation dose of 200 Monitor Unit (MU) or 2 Gy prescribed dose. Note that the gantry and collimator angle were positioned at 0° vertically oriented, pointing down at the couch table and the distance between source and phantom surfaces (SSD) was equal to 80 cm. A 30 cm x 30 cm x 20 cm rectangular cuboid water phantom (GAMMEX RMI®, Middleton, WI, U.S.A) was used in this study and was placed in an irradiation area at position of isocenter with radiation field size as 10 cm x 10 cm. The CD badges were placed at five different depths: 0, 2.5, 5, 10 and 20 cm from the phantom surface as shown in Figure 2. The phantom was exposed to the radiation for three times.

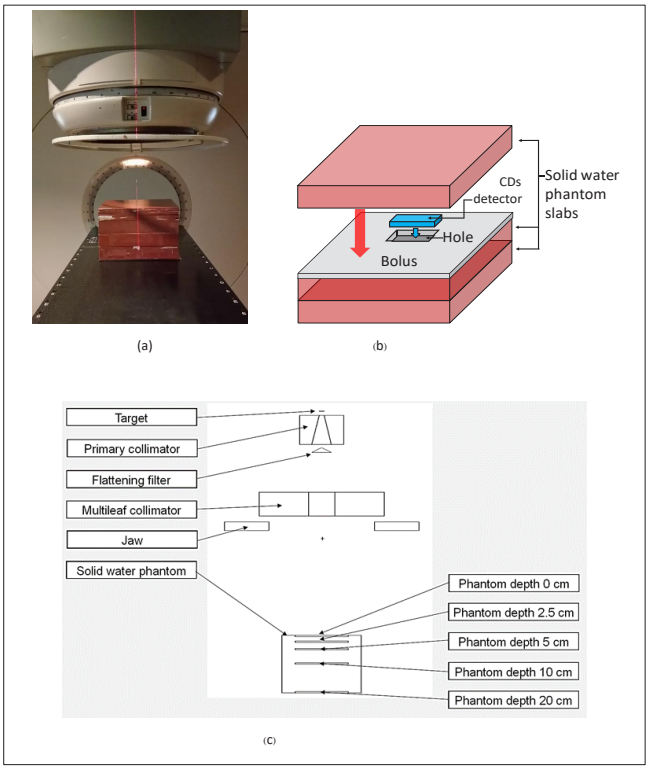


***Figure 2***. *Irradiation set up (a) in room with (b) hole of bolus, and (c) side view illustrating diagram of irradiation set up.*

**Chemical etching on CDs detector**

An etching chemical for polycarbonate track detectors used in this study was a mixed solution called PEW[12, 13] which was composed of 15%, 40% and 45% of potassium hydroxide (KOH), ethanol ($C_2H_5OH$) and water ($H_2O$), respectively. After irradiations, the CDs track detector badges were etched in PEW solution at 60±2 °C, 70±2 °C and 80±2 °C. The etching time was set from 0 to 24 hours. After etching, the badges were washed with 56 % ethanol and deionized (DI) water, and subsequently dried in dry (or dehumidified) air at room temperature. Then the etched track (etch pit) images generated on CDs track detector at position of 4. Five randomly chosen areas of 2.65 $mm^2$ from PMMA converter were counted for several tracks using a digital microscope with 100X magnification. Subsequently, the track density was calculated to find the most optimal chemical etching conditions.

**Fast neutron dose calibration**

The CDs track detector badges were irradiated with the neutron irradiation facility equipped with a 50 Ci $^{241}$AmBe neutron source at Thailand Institute of Nuclear Technology or TINT. The irradiation times were adjusted to achieve neutron doses ranging from 500 µSv to 100 mSv. The experimental setup was shown in Figure 3. After irradiation the badges were etched with optimal conditions and track densities were subsequently calculated.

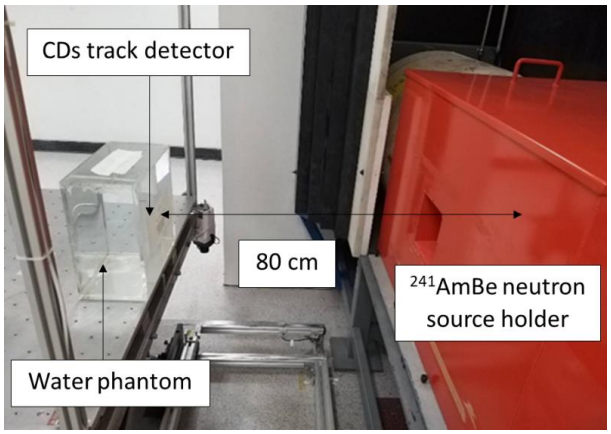


***Figure 3***. *Fast neutron dose calibration set up.*

**Comparison of fast neutron equivalent dose from CDs track with CR-39**

The statistical method of independent t-test with *p* value equal to 0.05 was used to compare calculated neutron equivalent dose of CDs detector and CR-39 detector.

## Results

**Optimization of chemical etching parameters of CDs detector**

Track densities as a function of chemical etching time at various PEW solution temperatures are shown in Figure 4. At temperature of 60 °C, the track densities gradually increase with increasing etching time and reach the maximum at about 14 hours. Similar behaviors were observed in case of 70 °C and 80 °C when the maximums were found at 10 hours and 20 hours, respectively. While longer etching time is needed to retrieve the tracks formed at greater depth, the tracks formed near the surface are worn away in the process. As a result, the track densities start to decline as the etching times increase. It is important to point out the effect of increasing PEW solution temperature. At temperature of 80 °C, the corroding reaction takes place at a faster rate and directly contributes to a number of observed tracks which are less than a number of tracks actually score. Based on these preliminary results, the chemical etching parameters for this study are the PEW solution temperature of 60 °C and the etching time of 14 hours. The 100X magnification microscopic images of tracks attributed from the CDs track detector at various etching time in PEW solution at 60±2 °C as shown in Figure 5. Nevertheless, etching condition at temperature of 50 °C should be done to consider the optimum parameter.

The CD track detector badges, which were previously irradiated at TINT to receive a number of different neutron doses were etched at specified conditions to study the relationship between track densities and equivalent doses. As expected, the track density is proportional to equivalent dose as shown in Figure 6. and their relationship can mathematically be explained by a power equation: $y=5E\text{-}08x^{2.2988}$ ($R^2=0.9618$). This was found to be in contrast to a number of studies[14, 15] which indicate linear relationship between track density and neutron equivalent dose. A reason for this discrepancy was thought to be a wide range of neutron energy, from 0.048 to 96.4 mSv, considered in this study. The CD track detectors are likely to have different response functions across this wide range of neutron energy. As a result, a power relationship is obtained when attempting to fit all data with one function. The dose calibration had been performed at both low and high dose, the result would be more conformed with other mentioned studies. However, large standard deviation of track densities was observed that at high dose due to an increasing likelihood of counting errors. A number of repetitions can be increased to reduce statistical errors of track density observed in this study.

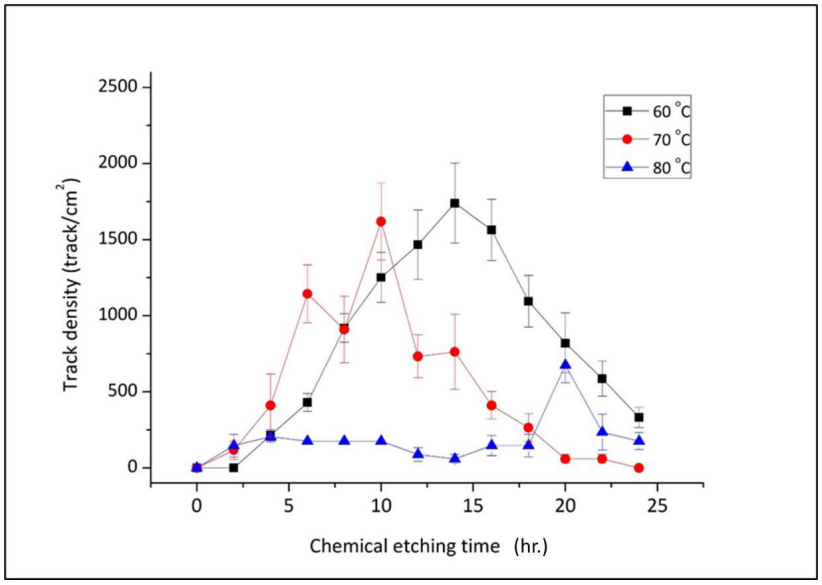


***Figure 4***. *Average track density (Track/cm$^2$) as a function of chemical etching time in CDs track detectors etched in PEW solution at 60°C, 70°C and 80°C.*

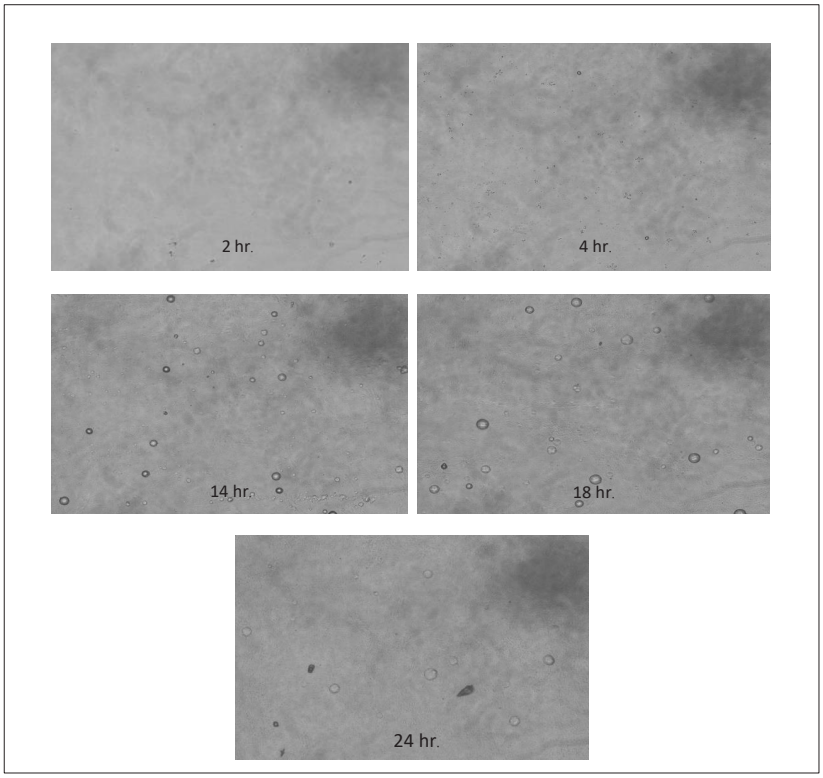


***Figure 5***. *The 100X magnification microscopic images of tracks obtained from the CDs track detector at various etching time in PEW solution at 60±2 °C.*

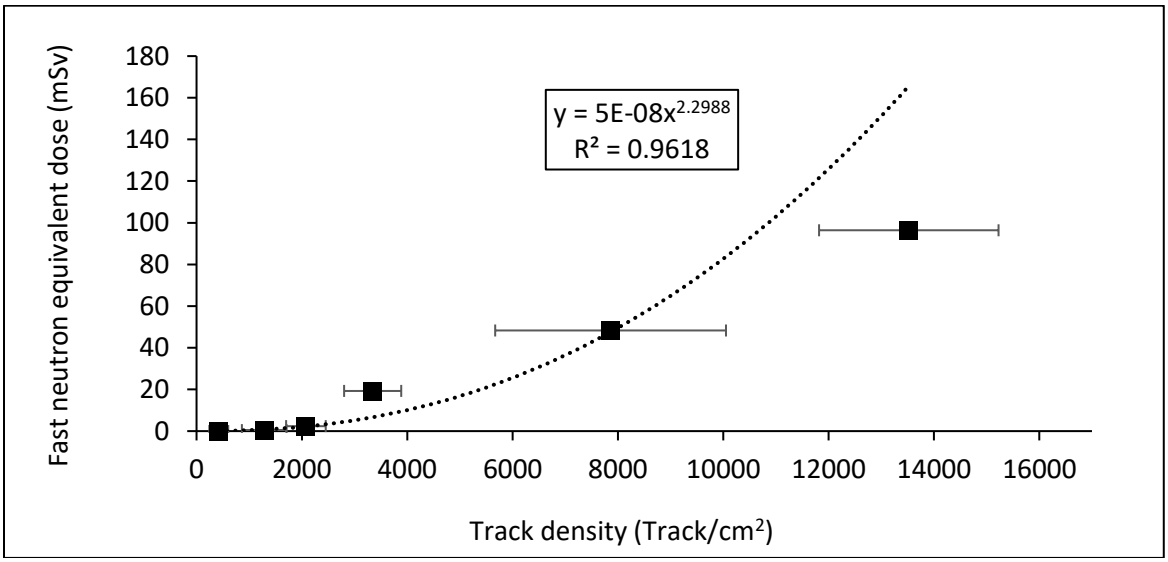


***Figure 6***. *Relationship between the track density and the fast neutron equivalent dose, obtained from 241AmBe neutron source.*

**Comparison of fast neutron equivalent dose from CDs track with CR-39**

Table 1 shows equivalent doses from fast neutrons as a function of depths in the water phantom using the CD track detector and CR-39 detector. The equivalent doses have high values at the surface, decrease at the depth of 2.5 cm and reach their maximums at the depth of 5 cm.

However, results from this study are different from those from other studies[16] because different LINACs in all studies have different configurations which may lead to different neutron spectrums and intensities. The maximum equivalent doFses at the surface for the CD track detector and CR-39 detector can be explained by the fact that the fast neutron converters in both cases can effectively produce protons which can tally permanent tracks on the phantom surface. As the fast neutrons continue their journey deeper into the water phantom, they are expected to lose energy due to collision or to get absorbed by hydrogen. These phenomenons dominate fast neutrons in the region from the surface to the depth of 5 cm, causing equivalent doses to decrease. Nonetheless, some LINACs are able to produce fast photo neutrons which can penetrate deeper into the water phantom. These photo neutrons play an important role in making the equivalent doses at 5 cm the highest. Statistically, independent t-test between the CD track detector and CR-39 detector reveals that equivalent doses at the phantom depths of 0, 2.5, 5 and 20 cm are not significantly different with a p value equal to 0.05. However, the results between the two cases are significantly different at the phantom depth of 10 cm.

Mean free path of neutrons from a 10 MV LINAC Model Elekta Synergy with an average energy of 2 MeV in water is about 4 to 5.5 cm.[17] Since the neutrons are expected to travel approximately 4 to 5.5 cm before undergoing any reaction with the water medium, both CD track detector and CR-39 detector register maximum equivalent doses at the phantom depth of 5 cm and score lower equivalent doses as it is getting deeper into the water phantom.

Shagholi N *et.al*.[18] evaluated equivalent doses on a tissue-like material from neutrons generated from LINAC Elekta at two distinct energies of 10 and 18 MV. The study measured equivalent doses at various depths: 0, 1, 2, 2.5, 3.3, 4, 5 and 6 cm, using TLD600 and TLD700 and compared them to equivalent doses calculated by MCNP code. The study by Shagholi N *et.al*. also exhibited a similar behavior of equivalent doses which increase from the surface, reach maximum at the depth of 5 cm and decrease at further depths. Therefore, this early study of using the CD track as a fast neutron detector has shown a promising sign to an innovative and economical approach for measuring collateral equivalent doses in cancer treatment.

**Table 1** Fast neutron equivalent dose as a function of depth (d) in the solid water phantom using CD track detector and CR-39 detector.

| Phantom depth (cm) | Fast neutron equivalent dose (mSv/Gy) | |
|---|---|---|
| | CDs track detector | CR-39 detector |
| 0 | (1.32±0.02) E-01 | (1.28±0. 77) E-01 |
| 2.5 | (1.14±0.01) E-01 | (1.10±0.05) E-01 |
| 5 | (1.32±0.05) E-01 | (1.63±0.85) E-01 |
| 10 | (3.70±0.2) E-02 | (1.28±0.44) E-01 |
| 20 | (2.50±0.4) E-02 | (5.70±5.70) E-02 |

## Conclusion

The CD track, whose foundation material is polycarbonate, together with PMMA and cadmium sheet, which etched with PEW solution at 60±2 °C, is proved to be reasonably accurate and affordable for measuring equivalent doses from fast neutrons generated from LINAC. In addition, the technique helps address a problem with electronic waste to some degree. An immediate future work to further develop the technique will include an investigation of the efficiency of PMMA sheet as a fast neutron converter. Neutron dose calibration should be done seperately for low and high neutron energy range for better precision and accuracy.

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