Comparison of Hi-Art Tomotherapy Machine Outputs Using AAPM TG-148 and IAEA TRS 483 Codes of Practice

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Abstract. Comparison of Hi-Art Tomotherapy Machine Outputs using AAPM TG-148 and IAEA TRS 483 Codes of Practice. This paper describes a short history and technological aspect from a Hi-Art tomotherapy machine. The comparison between the tomotherapy machine and conventional linear accelerator machine in the technological aspect and therapy features was also described. There are two codes of practice to determine the absorbed dose to water from the Hi-Art tomotherapy machine, The AAPM TG-148 and IAEA Technical Report Series No. 483. Determination of the absorbed dose to water was carried out at the machine specific reference condition by using the ionization chamber type of PTW TW 30013 SN 6367 volume 0.6 cc, and electrometer PTW Webline T10022/268. The results obtained show that the value of absorbed dose to water using the AAPM TG-148 was 8507 ± 2.4 mGy/minute and while using the IAEA TRS 483 the value of absorbed dose to water was 8485 ± 2.4 mGy/minute. The comparison result of the determination of the absorbed dose to water using AAPM TG-148 and IAEA TRS 483 protocol has a deviation of 0.2%.

1. Introduction

Radiotherapy is one option for treating cancer beside surgery and chemotherapy. The data shows that radiotherapy had an important role in the treatment and cure of cancer [1]. The goals of radiotherapy are to provide a measurable dose to a particular target volume to cure the tumor cell with a minimal side effect for normal tissue [2]. Radiotherapy was very helpful for the patient to curing their cancer/tumor.

Teletherapy machine that usually used in Indonesia is Cobalt-60 and linear accelerator machine. The use of cobalt-60 for the medical services is relatively cheaper and simpler but has some lacks and constraints in the operation, which was a low activity and the presence of radioactive waste, making the use of cobalt-60 teletherapy machine began to be abandoned in favor of medical linear accelerator machine. In 2008 the number of radiotherapy services known in Indonesia is as many as 22 service centers with a total of 17 of cobalt-60 and 10 medical linear accelerators [1]. Along with the needs of healthcare facilities, the number of radiotherapy centers in Indonesia in 2014 is rising to 27 service centers with 18 cobalt-60 teletherapy machines, 23 medical linear accelerators and 1 gamma knife. Per May 2018, the number of the radiotherapy service turned into 42 service centers with 25 cobalt-60 teletherapy machine, 40 medical linear accelerators, and two gamma knife.
In the year 2016 National General Hospital Dr. Cipto Mangunkusumo installed a helical Hi-art Tomotherapy machine. Hi-art tomotherapy machine is a medical linear accelerator with 6 MV photon beam. The therapy modalities with tomotherapy machine are new and the first in Indonesia. The Hi-Art tomotherapy machine can be seen in Figure 1 below.

The tomotherapy machine has a different principle of works with the conventional medical linear machine. The use of helical in this machine is to show that the gantry on fixed position and the patient table is move during the patient treatment. While was on a conventional medical linear accelerator gantry moves and patients table on a fixed position. Hi-Art tomotherapy machine has a treatment mode slice by slice (tomo) and spiral shaped. Some differences from the tomotherapy machine with the conventional medical linear accelerators can be seen in Table 1 below.

**Table 1.** The difference between the tomotherapy machine with the conventional medical linear accelerator

| Technology            | Conventional Medical Linear Accelerator | Tomotherapy Machine       |
|-----------------------|-----------------------------------------|---------------------------|
| Flattening filter     | Use                                     | Not use                   |
| Maximum Field Size    | 40 cm x 40 cm                           | 5 cm x 40 cm              |
| SSD                   | 100 cm                                  | 85 cm                     |
| Field Size indicator  | Light indicator                         | None                      |
| Detector              | None                                    | Xenon Detector Array      |
| Computed Tomography   | KVCT                                    | MVCT                      |
| Unit                  | cGy/MU                                  | cGy/minute                |

Every medical linear accelerator should be measured in accordance with the rules of BAPETEN No. 1 the year 2006. In the year 2016, Assef et.al. have measured the absorbed dose to water of tomotherapy machine using the code of practice AAPM TG-148 that recommended by the IAEA and the AAPM [3]. The measurement was carried out at machine specific reference. AAPM TG-148 described the value of $k_Q$ on the static field and machine specific reference condition.

In November 2017, IAEA issued a protocol IAEA Technical Report Series (TRS) 483: Dosimetry of small Static Fields Used in External Beam Radiotherapy an International - Code of Practice for Reference and Relative Dose Determination. On the IAEA TRS 483 discussed regarding the value of $k_Q$ to determine the absorbed dose to water of the tomotherapy machine at a specific reference condition with SSD 85 cm and field size 5 cm x 10 cm.

This paper describes a short history and a few aspects from Hi-Art tomotherapy machine and also comparison on the determination of absorbed dose to water using the code of practice AAPM TG-148 and IAEA TRS 483. The comparison between the tomotherapy machine and conventional linear accelerator machine in the technological aspect and therapy features was also described.

*Figure 1. Hi-Art Tomotherapy Machine at RSCM Jakarta*
1.1. A Short History of Tomotherapy Machine

Helical tomotherapy machine was developed by Thomas Rockwell Mackie, Ph.D. from the University of Wisconsin, Madison, USA. The development of this tomotherapy machine was expected to be a solution from the conventional linear accelerator machine’s problem. These problems are [4]:

- The limitation of target dose that can be delivered due to the presence of neighboring sensitive structures
- Verification of the correct beam shape and position simultaneously while ensuring that the patient is positioned correctly
- Limitation in the safety of dynamic therapy due to the possibility of collision between the patient and the treatment unit.

The use of a continuous motion system of the slip-ring gantry for radiotherapy was introduced by this tomotherapy machine. Tomotherapy has a system that can modulate a beam using a fan beam and also has a temporarily modulated multileaf collimator system (binary MLC). On 21 August 2002, the University of Wisconsin treated the first patient the first man with bone metastasis cases [5]. Through the first patient treatment, it can be known the MVCT characteristics. The MVCT features still needed further development for optimal performance.

Helical tomotherapy has technological development and it’s applications for another disease’s treatment. Tomotherapy has a new system called adaptive therapy system. This system is able to display and analyze the dose given to the patient, and also to calculate the treatment dose.

1.2. The Main Component of Tomotherapy Machine

The main components of the Hi-Art tomotherapy machine include the linear accelerator 6 MV, multileaf collimator, megavoltage computed tomography (MVCT), data acquisition system, beam stopper, xenon detector, pulse forming network modulator, and computer control. The main components of the Hi-Art tomotherapy machine can be seen in this figure below.

![Figure 2. Main component of tomotherapy machine](image)

1.2.1. Radiation Source: Linear Accelerator Medic. The radiation source for tomotherapy is linear accelerator 6 MV. The linear accelerator machine was placed on a ring gantry that can rotate 360° continuously. To produce a homogeneous beam in the conventional medical linear accelerator, the machine should have a flattening filter that placed on the beam path. Flattening filter is a cone which made of a material with a high atomic number. On helical tomotherapy machine, flattening filter is not used, thus the provisions of flatness and symmetry on conventional photon beam are not applied.
Another purpose by not using this flattening filter is the radiation quality will be lower but will increase the dose rate.

1.2.2. **Multi-leaf Collimator.** The beam’s shape from this tomotherapy machine is a fan beam that is produced by a set of collimating jaw with a maximum transverse length of 40 cm and a maximum width of 5 cm longitudinal. The beam passes through 64 binary collimator blades that controlled using pneumatically.

1.2.3. **Megavoltage Computed Tomography (MVCT).** As described in Table 1, one of the differences between a tomotherapy and a conventional medical linear accelerator machine is the radiation source for imaging process. On the conventional medical linear accelerator machine, imaging process was carried out using an additional radiation source with a kilovoltage x-ray machine (KVCT). While on the tomotherapy machine, the radiation source for the imaging process is photon beam with potential voltage for the linear accelerator is reduced from 6 MV to 3.5 MV. To get a fluoroscopy image, an array xenon detector was placed on the gantry opposite the linear accelerator. Beside for clinical purposes, MVCT can also be used for assistive devices to place the detector accurately at the desired position. The measured dose during this MVCT must be less than 4 cGy.

1.2.4. **Beam Stopper.** The function of the beam stopper is for the absorber of the main radiation beam emitted by the radiation source (6 MV linear accelerator). The absorbent radiation beam is placed on the gantry opposite with the radiation source. The position of the beam stopper is on the 74 cm from the machine isocenter. The beam stopper will be effective with the dimensions of the tin plate that defines as 89 cm long, 23 cm wide and 13 cm thick [6].

1.2.5. **Xenon Detector and Data Acquisition System.** The detector used by tomotherapy is the xenon ionization detector. The detector is arranged in such a way as to form an arrangement of xenon gas filling detector systems. This system consists of 738 xenon gas filling detectors and placed opposite the radiation source [7]. The diagnostic results obtained will be continued as input to the tomotherapy software. The main purpose of installing Xenon detector arrays for MVCT is for verification of the delivery and reconstruction dose by the tomotherapy system.

1.3. **The Differences of Techniques/Processes in Tomotherapy Machine and Linear Accelerator**

Based on the explanation above, there is a significant difference between tomotherapy and conventional medical linear accelerator on the technique or treatment process. The following are some of the differences:

| Table 2. The differences of techniques/processes in tomotherapy machine and linear accelerator [8] |
|---------------------------------------------------------------|
| Process or Technique                                      | Conventional Linear Medical Accelerator | Tomotherapy Machine |
| Conformal radiation therapy                                | 3-D treatment planning                  | Inverse treatment planning |
| Set-up verification                                        | Laser alignment; Port films or electronic portal imaging | CT projections to obtain detailed anatomical information |
| Delivery modification                                      | Repositioning of the patient            | Adapt delivery according to patient displacement |
| Beam alignment verification                                | Port films or electronic portal imaging  | Acquire CT scans before, during or after treatment |
| Delivery verification                                      | Electronic portal imaging               | Compute the energy fluence actually delivered to the patient on a pulse by pulse basis |
| Dose reconstruction                                        | None                                   | Superimpose on a CT representation the dose actually deposited in the patient during treatment and compare to the planned dose |
2. Method and Materials

2.1. Determining The Absorbed Dose to Water of Tomotherapy Machine

The use of the AAPM TG-148 protocol is based on the absence of $k_Q$ values for the tomotherapy machine at protocol TRS 398 that usually use for the determination of absorbed dose to water for conventional linear accelerator medic. The conventional linear accelerator medic has $K_Q$ values for reference condition at field size 10 cm x10 cm, SSD 100 cm, and using a flattening filter, while the field size of tomotherapy is 5 cm x 40 cm, SSD 85 cm and using flattening filter free. In the protocol TRS 398, a $K_Q$ value for each detector with various volumes has been provided on a standard field size 10 cm x 10 cm, SSD 100 cm and using a flattening filter, valid for electron beam or photon beam. So based on the machine requirements to determine the $K_Q$ value on the tomotherapy machine, an approach is used in accordance with the AAPM TG-148 protocol.

The absorbed dose to water for the photon beam produced from the tomotherapy machine at the reference depth is given by equation 1 below [9].

$$D_{w,Q_{mar}}^{f_{mar}} = M_{f_{mar}}^{Q_{mar}}N_{D,w,Q_0}k_{Q_0,Q_{mar}}k_{f_{mar},f_{mar}}$$

Where

- $Q$: is the radiation beam quality [%$dd(10)$] of the conventional reference field size of 10 cm x 10 cm at 100 cm SSD according to TG-148 protocol.
- $Q_{mar}$: is the radiation beam quality [%$dd(10)$] of the machine specific reference field size $f_{mar}$ (5 cm x 10 cm field at 85 cm SSD)
- $M_{f_{mar}}^{Q_{mar}}$: is the corrected reading of the dosimeter for the field $f_{mar}$
- $N_{D,w,Q_0}$: is the absorbed dose to water calibration factor for a reference quality $Q_0$
- $k_{Q_0,Q_{mar}}$: is the beam quality correction factor for the quality $Q$ of the conventional reference field $f_{mar}$ (10 cm x 10 cm at 100 cm SSD).
- $k_{f_{mar},f_{ref}}$: is the factor to correct for the differences condition of field size, geometry, phantom material, and beam quality of the conventional reference field $f_{ref}$ and the machine specific reference field $f_{mar}$

Thomas R. Mackie describes a method to determine the correction factor. The function of the correction factor is to correct the difference between the conditions of field size, geometry, phantom material and beam quality of the conventional reference field and the machine specific reference using a third order polynomial expressed in equation 2 [10].

$$%dd(10)_{(HTT-100)} = 1.35805.(%dd(10)_{(HTT-100)}) \times 244.493.(%dd(10)_{(HTT-100)})^2 + 14672.98.(%dd(10)_{(HTT-100)})^3 - 293479.4$$

The $k_Q$ value can be obtained using Table 2. The $k_Q$ values are nearly constant for the most commonly cylindrical ionization chambers found in TG-148 and Thomas et al, varying from 0.999 to 0.995.

Table 3. Values of KQ for photon beams as a function of the beam quality %$dd(10)$x[10]

| Ion Chamber       | Beam Quality Specifier [%$dd(10)$] | $K_Q$     |
|-------------------|----------------------------------|-----------|
| PTWN3001 0.6 cc   | 58                               | 0.996     |
| PTWN3004 0.6 cc   | 63                               | 0.992     |
| PTWN3004 0.6 cc   | 66                               | 0.992     |
Assef F. F et al. have been done for determining the absorbed dose to water for the machine specific reference field from a Hi-Art helical tomotherapy machine using three different ionization chambers [4]. The measurement of the percentage depth dose has been carried out at the source-to-detector distance of 85 cm and a field size of 5 cm x 10 cm. The measurement of the absorbed dose to water has been done using standard detector Farmer 0.6 cc TW 30013.

Table 4. The Result of Determination of Absorbed Dose to water using AAPM TG-148 [3]

| Detektor | $M_Q$ (nC) | $N_{D,w}$ (mGy/nC) | $k_Q$ | PDD$_{10}$ (%) | $D_{W,Q}(Z_{max})$ (mGy/minute) | $D_{W,Q\text{raw}}$ (mGy/minute) |
|----------|------------|---------------------|-------|----------------|---------------------------------|---------------------------------|
| A 1 SL   | 8.330      | 603.3               | 0.9985| 5018           | 58.87                           | 8524 ± 2.5 %                   |
| PTW TW30013 | 92.390   | 54.27               | 0.9985| 5006           | 58.87                           | 8503 ± 2.5 %                   |
| PTW 31016 | 2.009     | 2516                | 0.9980| 5045           | 58.87                           | 8569 ± 2.5 %                   |

These results indicate that the measurements using the three detectors get insignificant differences. The difference in measurement with a detector is not greater than 0.5% for each detector. Determination of the absorbed dose to water using the AAPM TG-148 protocol recommended by the IAEA and AAPM.

In November 2017, The IAEA issued the IAEA TRS 483: Dosimetry of small Static Fields Used In External Beam Radiotherapy - an International Code of Practice for Reference and Relative Dose Determination. IAEA TRS 483 describes $k_Q$ value for the tomotherapy machine at machine specific reference condition. Determination $k_Q$ value for tomotherapy is different from a conventional linear accelerator machine.

Absorbed dose to water for conventional linear accelerator medic were determined using radiation quality ($Q$) can be determined using the ionization chamber which calibrated in absorbed dose to water for Co-$^{60}$ $N_{0,w}$ (gamma ray). The calculation has been doing by the following equation [11].

$$D_{W,Q} = M_Q \cdot N_{D,w,Q} \cdot k_Q$$  \hspace{1cm} (3)

Where

- $D_{W,Q}$ : Absorbed dose to water with radiation quality $Q$ (mGy)
- $M_Q$ : Raw data dosimeters corrected for temperature, air pressure, polarity, $k_{pol}$ and ion recombination, $k_i$ (nC)
- $N_{D,w}$ : Detector calibration factor for Co-$^{60}$ gamma rays (mGy/nC)
- $k_Q$ : Correction factor for photon beam radiation quality from the detector

In the IAEA TRS 483, the equation to determine the absorbed dose to water is essentially the same with the equation in AAPM TG-148. The $k_Q$ value in IAEA TRS 483 was determined based on calculations using the Monte Carlo program for machine specific reference conditions for the tomotherapy machine. These conditions include parameters:

Table 5. Reference condition for Tomotherapy machine in IAEA TRS 483 [11]

| Parameter                        | Reference value or reference character |
|----------------------------------|----------------------------------------|
| Phantom Material                 | Water                                  |
| Phantom shape and size           | At least 30 cm x 30 cm x 30 cm          |
| Chamber type                     | Cylindrical                            |
| Measurement depth $z_{\text{eff}}$| 10 g/cm$^2$                             |
| Position of the reference point  | Measurement at depth $z_{\text{eff}}$   |
| of chamber                       |                                        |
| SSD/SDD                          | 85 cm                                  |
| Field size                       | 5 cm x 10 cm                           |
The $k_Q$ value in the table can be directly used to determining the absorbed dose to water because the condition has been adjusted for the tomotherapy machine. In IAEA TRS 483 for PTW 30006/30013 Farmer ionization detector, $k_Q$ value was obtained at 0.995. The measurement was carried out using PTW TW 30013 SN 6367 volume 0.6 cc and electrometer PTW Webline T10022/268.

3. Result and Discussion
In Table 4 below, the average reading from the electrometer is 92.97 nC for measurements per 60 seconds. The $k_Q$ value is obtained from IAEA TRS 483 for a value equivalent to the specific reference for the tomotherapy machine. The absorbed dose to water at the static conditions of the tomotherapy machine was $8485 \pm 2.4$ mGy/minute.

| Code of Practice | Detector   | $M_Q$(nC) | $N_{D,w}$(mGy/nC) | $k_Q$ | PDD$_{10}$ (%) | $D_{max}(Z_{max})$ (mGy/minute) |
|------------------|------------|-----------|-------------------|-------|---------------|----------------------------------|
| IAEA TRS 483     | TW30013    | 92.97     | 53.92             | 0.9950| 58.98         | 8485 ± 2.4 %                     |
| AAPM TG-148      | TW30013    | 92.97     | 53.92             | 0.9975| 58.98         | 8507 ± 2.4 %                     |

If the determination of the absorbed dose to the water is carried out using the AAPM TG-148 protocol on the same data, then the $k_Q$ value will be obtained at 0.9975 and the value of absorbed dose to the water was $8507 \pm 2.4$ mGy/minute.

The comparison result of the determination of the absorbed dose to water using AAPM TG-148 and IAEA TRS 483 protocol has a deviation of 0.2%. The deviation obtained does not show a significant difference. The differences between AAPM TG-148 and IAEA TRS 483 were so close, because it was calculated by using the same principal. The calculation $k_Q$ using Monte Carlo program uses that reference condition for the tomotherapy machine. Both protocols can be used to determine the absorbed dose to water in the static conditions of the tomotherapy machine.

4. Conclusion
Tomotherapy machine has different technologies with conventional linear accelerator medic. The unique system of tomotherapy has a multi-bladed collimator (binary MLC), continuous irradiation with a slice per slice irradiation capability, 360° rotating gantry, megavoltage computed tomography (MVCT) and applied adaptive therapy system. The field size of the tomotherapy machine are 5 cm x 10 cm and 5 cm x 40 cm. Because the size of this field size, the cases that can be handled by tomotherapy machine are different from conventional linear accelerator medic.

The protocols that can be used to determine the absorbed dose to water in the static conditions of the Tomotherapy machine is AAPM TG-148 and IAEA TRS 483. The measurement of photon beam uses the PTW 30006/30013 Farmer ionizing and webline electrometer T10022/268. The value of the absorbed dose to water which determined using AAPM TG-148 protocol was $8507 \pm 2.4$ mGy/minute, while determined using IAEA TRS 483 protocol the absorbed dose to water was $8485 \pm 2.4$ mGy/minute. The comparison result of the determination of the absorbed dose to water using AAPM TG-148 and IAEA TRS 483 protocol has a deviation of 0.2%. Both protocols can be used to determine the absorbed dose to water in the static conditions of the tomotherapy machine.

5. Acknowledgment
The authors would like to acknowledge to the staff of the Radiotherapy Unit of Dr. Cipto Mangunkusumo National General Hospital for help with the tomotherapy Hi-Art measurements.
6. References

[1] Eri Hiswara 2017 Prosiding PPI – PDIPTN (Yogyakarta - PSTA BATAN) p 47–52
[2] Diah FI and Anggraita P 2010 Prosiding PPI – PDIPTN (Yogyakarta - PSTA BATAN) p 166–75.
[3] Assef F.F and S I Sunaryati 2017 Prosiding PPI – PDIPTN (Yogyakarta - PSTA BATAN) p 413–18.
[4] Mackie TR, Holmes T, Swerdloff S, Recwerdt P Deasy JO, Yang J, Paliwal B and Kinsella T Med Phys 20 1709–19.
[5] Mackie TR 2006 Phys Med Biol 51 R427-53.
[6] S. Baechler, F.O. Bochud, D. Verellen, R. Moeckli 2007 Shielding requirements in helical tomotherapy Phys Med Biol 52 5057–67.
[7] Podgorsak EB 2005 Radiation Oncology Physics: A Handbook for Teachers and Students (Vienna – International Atomic Energy Agency)
[8] Van Dyk J, Kron T, Bauman G, Battista J, Bauman G and Battista JJ 2002 Phys Canada 58 79–86.
[9] International Atomic Energy Agency 2017 Dosimetry of Small Static Fields Used in External Beam Radiotherapy: An Code of Practice for reference and Relative Dose Determination (Vienna – International Atomic Energy Agency)
[10] Langen KM, Papanikolau N, Balog J, Crilly R, Followill D, Goddu SM, Grant W, Olivera G, Ramsey CR and Shi C. 2010 Med Phys 37 4817–53.
[11] Pedro Andreo, David T Burns, Klaus Hohlfeld, M Saiful Huq, Tatsuaki Kanai, Fedele Laitano, Vere Smyth SV 2006 Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry based on Standards of Absorbed Dose to Water. (Vienna – International Atomic Energy Agency)