Journal of BUON **15:** 373-377, 2010
© 2010 *Zerbinis Medical Publications. Printed in Greece*

ORIGINAL ARTICLE

Impact of pulse forming network and injection current parameters on output and energy variations of helical tomotherapy

A. Gutierrez, S. Stathakis, C. Esquivel, Y. Liu, Y. Zhai, C. Shi, N. Papanikolaou

Department of Radiation Oncology, University of Texas Health Science Center at San Antonio, San Antonio, TX, USA

Summary

Purpose: *In this study, an experiment was devised to establish the dependency of the impact of pulse forming network (PFN) and injection current (IC) parameters on output and energy variations of helical tomotherapy (HT) on the radiation beam output and energy.*

Methods: *HT has unique radiation beam characteristics due to the absence of a flattening filter. As with conventional linear accelerators, the machine output and energy should be within a ±2% tolerance according to published studies. However, because a dose servo is not utilized in a HT unit, these parameters may drift out of the ±2% tolerance due to various reasons such as high machine temperatures. With this in mind, physicists and engineers must adjust certain machine parameters to reset the output and energy to within the tolerance of the commissioned baseline. Two parameters commonly adjusted are: PFN voltage (V_{PFN}) and IC voltage (V_{IC}).*

Results: *Results showed that the HT unit possesses different working zones defined by the V_{PFN} and V_{IC} parameter settings. The working zones were classified into 5 zones: 1) low dose rate zone - radiation dose rate much lower than nominal dose rate and machine cannot run due to low dose rate fault; 2) normal dose rate zone - dose rate is within tolerance of nominal dose rate and machine can run without dose rate fault; 3) dose rate failure during treatment zone - dose rate within the tolerance of the nominal dose rate however machine interrupts during treatment due to dose rate fault; 4) high dose rate zone - dose rate is higher than nominal dose rate and machine cannot run due to high dose rate fault; and 5) inoperable dose rate zone - dose rate is much higher than the nominal dose rate and machine cannot run.*

Conclusion: *The results of this study may provide a quick guide for physicists to adjust their HT unit V_{PFN} and V_{IC} values in order to reset the radiation beam output and energy back to within the tolerance of the commissioned baseline.*

Key words: energy, injection current, output, PFN, tomotherapy

Introduction

The helical tomotherapy Hi-Art^{TM} (HT) unit made by TomoTherapy Inc. (Madison, WI) is a specifically designed modality for intensity modulated radiation therapy (IMRT) treatments [1]. The radiation beam output and energy are recommended to be within a ±2% tolerance of the commissioned values [2]. However, fluctuations in output and energy may happen when a component is either replaced or deteriorating due to usage. Once this occurs, physicists need to tune the accelerator output machine (AOM) parameters to ensure the radiation output and energy are equivalent to the commissioned values. Among those AOM parameters, two parameters are crucial in the tuning of a HT unit, namely V_{PFN} and V_{IC}.

The PFN serves to store the energy for a single pulse and deposit the energy in the form of a specified pulse shape into the microwave source (magnetron for the HT unit) [3]. The V_{PFN} parameter controls the PFN pulse amplitude and the input current to the HT magnetron [4]. When the V_{PFN} is varied, the stored energy in the PFN changes and variations in the magnetron output power occur. This ultimately affects the accelerated electron energy. The V_{IC} controls the amplitude of the electron gun pulse [4]. When V_{IC} is increased or

Correspondence to: Sotirios Stathakis, PhD. MC 7889/Radiation Oncology, CTRC @ UTHSCSA, Ste G240, 7979 Wurzbach Rd., San Antonio, TX, 78229, USA. Tel: +1-210-450-1010, Fax: +1-210-616-5682. E-mail: stathakis@uthscsa.edu

Received 16/09/2009; Accepted 23/10/2009

decreased, the amount of injected electrons entering the linear accelerator increases or decreases, respectively. Therefore, the beam energy and output will be affected by changes in V_{IC}. Variations in both the V_{PFN} and V_{IC} can affect the radiation beam output and energy to different degrees.

Published literature indicates that a HT unit can maintain its calibration of output to within ±2% and energy to within ±1.5% over a period of at least 20 weeks [5]. Literature also suggests that for quality assurance purposes the HT output variations should be restricted to within ±2% of the long-term average output [2]. Hence, it is essential for a physicist and engineer to consistently reset the output and energy back to the tolerance of the calibration baselines to prevent treatment deviations – i.e. underdosing or overdosing the patient. This process is a complex task and often requires hours to completely adjust the machine parameters back to the ±2% tolerance range. However, it may be possible to adjust the HT beam output and energy quite efficiently by simply adjusting the V_{PFN} and V_{IC} parameters. To date, several papers have been published regarding HT unit quality assurance [2,5-12], but no publications have characterized the dependency of these two parameters on the radiation beam output and energy for a HT unit. In light of this, the present study sought to quantify the impact of variations of both V_{PFN} and V_{IC} values on the radiation beam output and energy of a HT unit in order to provide useful guidelines for HT users.

Methods

Tomotherapy quality assurance (TQA^{TM}) platform

The tomotherapy quality assurance (TQA^{TM}) software platform has been developed by TomoTherapy Inc. in order to qualitatively assess the tomotherapy unit [11]. TQA^{TM} is an integrated, web-based platform which uses the on-board monitor ion chamber and imaging detector data to extract the HT unit status. TQA^{TM} provides basic dosimetry modules such as a rotation variation, data acquisition system (DAS), file system information, step wedge static module, and data file transfer protocol (FTP) modules. The complete TQA^{TM} system consists of the software platform and corresponding hardware equipments. For example, the step wedge static module requires a specific hardware component (step wedge) as discussed below. The software allows users to save history data for off-line review and analysis. All the data collection for this study was performed using the pre-released TQA^{TM} platform (beta version).

Step wedge phantom and step wedge static module

A steel step wedge phantom has been designed by TomoTherapy Inc. which consists of 5 steps with a 30.0×69.7×19.5 mm^3 dimension for each step (Figure 1). The step wedge phantom along with the step wedge static module software monitors the HT system output, energy, jaw collimation, couch speed, and detector response consistency. The software platform utilizes the extracted post-procedure on-board dose monitoring system and imaging detector array data for analysis.

The step wedge static module from the TQA^{TM} software was utilized for the present experiment. After the procedure for the module is delivered using the step wedge phantom, the module algorithm uses the pulse-by-pulse data acquired through the on-board detector system to analyze the HT system radiation beam output, energy, jaw collimation, couch speed, laser setup accuracy, and detector response consistency within a single procedure. In this module, the procedure settings for the HT unit are set as follows: jaw setting is set to a 1.0 cm field width mode, all the multileaf collimators (MLCs) are open, and the couch speed is set to 1.0 mm/s. The linear accelerator is fixed at the vertical position (0 degrees) and remains stationary for the duration of the 200-second beam-on time.

When the radiation beam penetrates the 5 different thickness steps in the step wedge phantom, due to beam attenuation, the signals recorded on the on-board imaging detector system will show step wedge shape profiles. By comparing the measured profiles to a set of baseline profiles, the module can monitor the system output consistency. If a ratio of the different step profiles is calculated, the consistency of the beam energy

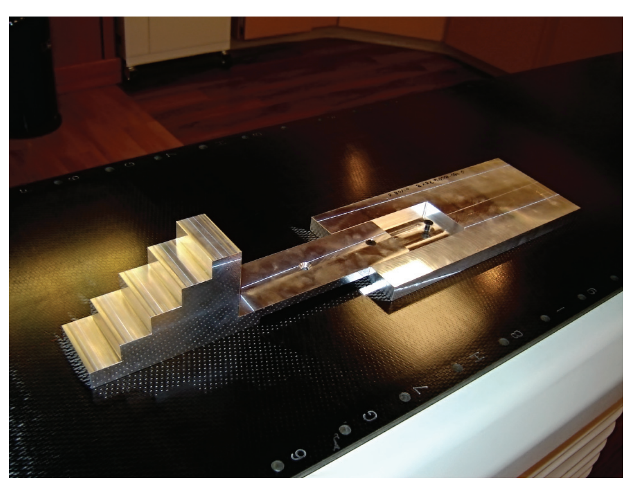

Figure 1. TomoTherapy TQA^{TM} steel step wedge phantom utilized in the study. The phantom consists of five steps with a 30.0×69.7×19.5 mm^3 dimension for each step. The phantom cantilevers on the front end of the tomotherapy treatment couch.

is also monitored. Since the couch speed is constant, the module monitors the couch speed consistency and couch positioning accuracy by detecting the attenuation profile center (for lateral position consistency) and width (for vertical position consistency and couch speed consistency). The step wedge static module includes additional functions; however, in this study, the goal was to focus primarily on the output and energy ratio data.

V_{PFN} and V_{IC} variation strategies

The HT system baseline was established based on the original commissioned parameter settings. For the HT unit tested, the AOM parameters were based on a V_{PFN} voltage of 4.04 V and a V_{IC} voltage of 3.54 V. These AOM parameter values produced an average dose rate of 880 MU/min as defined by the on-board monitor 1 (MU 1) for a 200-second static treatment. For different V_{PFN} and V_{IC} combinations, system faults may occur if parameters deviate from the commissioned baseline such as: (i) dose rate is too low fault; (ii) dose rate is too high fault; (iii) linac operates in an unstable state for a fixed amount of time but eventually causes either a dose rate too low or too high fault; or (iv) linac becomes inoperative. To initially establish the overall system working zones for different combinations of V_{PFN} and V_{IC}, both values were coarsely sampled from 3.0 to 5.0 V in 0.2 V increments.

Different combinations of V_{PFN} and V_{IC} do exist within the normal dose rate zone due to the fact that for the same dose rate both the accelerated electron numbers and energy may differ. Since the purpose of this study was to understand how to adjust the V_{PFN} and V_{IC} in the normal dose rate zone, for the tested HT unit, the normal dose rate zone was defined as the V_{PFN} ranging from 4.0 to 4.1 V and V_{IC} ranging from 3.5 to 3.7 V. Parameter settings outside of this range produced unstable zones (dose rate failure during treatment zone), zones with the potential to damage the HT unit (inoperable dose rate zone), zones which would not run due to low/high dose rate faults (low dose rate and high dose rate zone), or zones where V_{PFN} and V_{IC} values were different from the commissioned one and not recommended by the vendor (the other normal dose rate zones). Finer sampling of the V_{PFN} and V_{IC} parameter effects on output and energy were only performed inside the normal dose rate zone ($4.0 \leq V_{PFN} \leq 4.1$ and $3.5 \leq V_{IC} \leq 3.7$) with V_{PFN} and V_{IC} values sampled in 0.02 V increments. After the AOM parameters were adjusted, HT average dose rate and energy were re-evaluated experimentally using the step wedge system as the baseline for further experiments.

Results

Working zones defined by different V_{PFN} and V_{IC} pair

Figure 2 illustrates the overall working zones for a HT unit when varying the V_{PFN} and V_{IC} AOM parameters.

In Figure 2, the working zones were classified into 5 zones: 1) low dose rate zone - radiation dose rate much lower than nominal dose rate and machine cannot run due to low dose rate fault; 2) normal dose rate zone - dose rate is within tolerance of nominal dose rate and machine can run without dose rate fault; 3) dose rate failure during treatment zone - dose rate is within the tolerance of the nominal dose rate, however, machine interrupts during treatment due to dose rate fault (either high or low dose rate); 4) high dose rate zone - dose rate is higher than nominal dose rate and machine cannot run due to high dose rate fault; and 5) inoperable dose rate zone - dose rate is much higher than the nominal dose rate and machine cannot run once started.

Average dose rate changes due to the variations in V_{PFN} and V_{IC} values

Figure 3 shows the percentage change of the average dose rate as a function of percentage change in V_{IC}. For the average dose rate, changes in these parameters were linearly related to changes in V_{IC} values. This relationship was consistent for all V_{PFN} values evaluated. It was noted that a 1.0% increase in V_{IC} yields an average 1.4% increase in the average dose rate. Additionally, a 0.02 V increase in V_{PFN} yields an average 1.0% increase in the average dose rate.

The percentage change of the average dose rate as a function of the percentage change in V_{IC}, and V_{PFN}

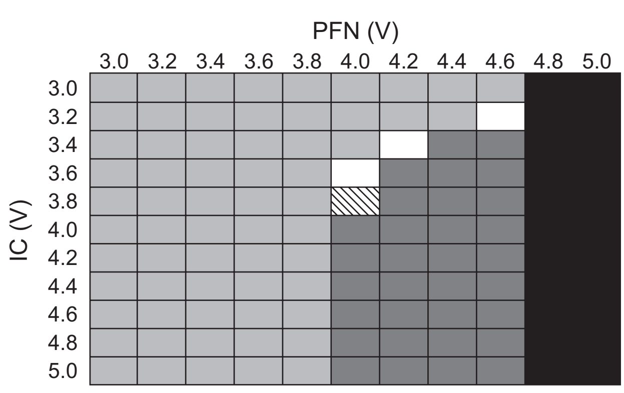

Figure 2. Working zones defined by V_{PFN} and V_{IC} settings are illustrated. Zones were defined as follows: low dose rate (light gray), normal dose rate (white), dose rate failure during treatment (lines), high dose rate (dark gray), and dose rate not permitted (black).

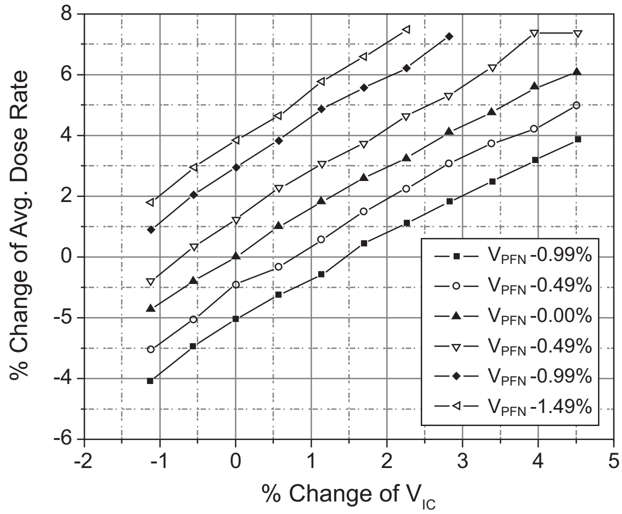

Figure 3. Percentage change of the average dose rate as a function of percentage changes of V_{IC} for the V_{PFN} values evaluated.

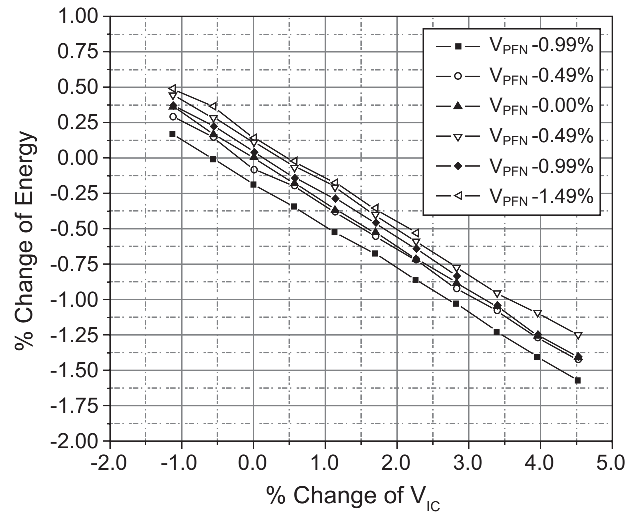

Figure 4. Percentage change of the energy ratio as a function of percentage changes of V_{IC} for the V_{PFN} values evaluated.

can be fitted using a 2nd order polynomial expressed as Equation (1):

$$\dot{D}\% = A*(V_{IC}\%)^2+B*(V_{PFN}\%)^2+C*(V_{IC}\%\times V_{PFN}\%)+D*V_{IC}\%+E*V_{PFN}\%+F$$

$$(A\ B\ C\ D\ E\ F) = (0.000\ \ -0.0397\ \ 0.0027\ \ -0.3060\ \ 0.1370\ \ 0.0093),\ (4.0 \leq V_{PFN} \leq 4.1 \text{ and } 3.5 \leq V_{IC} \leq 3.7)$$

where A, B, C, D, E, F are fit coefficients, $\dot{D}\%$ is the percentage change of the average dose rate relative to the baseline value, $V_{IC}\%$ is the injection current voltage percentage change relative to 3.54 V, and $V_{PFN}\%$ is the PFN voltage percentage change relative to 4.04 V. The A, B, C, D, E, F coefficients are calculated using a least squares fit and the mean squared error is 0.0015.

From Equation 1, the A coefficient is 0, and the B coefficient is almost one order higher in magnitude than the C coefficient. This fit indicates that $\dot{D}\%$ has less dependence on the $(V_{IC}\%)^2$ and $V_{IC}\%\times V_{PFN}\%$ terms than $(V_{PFN}\%)^2$ term.

Energy difference changes with V_{PFN} and V_{IC}

Figure 4 shows the percentage change of the energy ratio as a function of percentage changes of V_{IC} for the V_{PFN} values evaluated. Similar to the average dose rate, percentage changes in energy were linear with percentage changes in V_{IC} for all V_{PFN} values evaluated. A 1.0% increase in the V_{IC} value yielded an average 0.3% decrease in the energy ratio. Furthermore, changes in the energy ratio were more dependent on V_{IC} than V_{PFN} based on the fact that only a 0.5% variation in energy was noted when varying the V_{PFN} from 4.00 to 4.10 V, while a 2.0% change was noted when varying the V_{IC} from 3.5 to 3.7 V.

The percentage change of the energy as a function of the percentage change in V_{IC} and V_{PFN} can be fitted using a 2nd order polynomial expressed as Equation (2):

$$Energy\,\% = A'*(V_{IC}\%)^2+B'*(V_{PFN}\%)^2+C'*(V_{IC}\%\times V_{PFN}\%)+D'*V_{IC}\%+E'*V_{PFN}\%+F'$$

$$(A'\ B'\ C'\ D'\ E'\ F') = (-0.0598\ \ 0.1432\ \ 0.0524\ \ 1.6262\ \ 2.4255\ \ 0.1064),\ (4.0 \leq V_{PFN} \leq 4.1 \text{ and } 3.5 \leq V_{IC} \leq 3.7)$$

where the A′, B′, C′, D′, E′, F′ are fit coefficients. *Energy %* is the percentage change of the energy relative to the baseline, $V_{IC}\%$ is the injection current voltage percentage change relative to 3.54 V and $V_{PFN}\%$ is the PFN voltage percentage change relative to 4.04 V. The A′, B′, C′, D′, E′, F′ coefficients are calculated using a least squares fit and the mean squared error is 0.0308.

From Equation 2, the A′ and C′ coefficients for $(V_{IC}\%)^2$ and $V_{IC}\%\times V_{PFN}\%$ terms are one order in magnitude less than the B' coefficient for $(V_{PFN}\%)$^2 term which indicates that the Energy % has less dependence on the $(V_{IC}\%)^2$ and $V_{IC}\%\times V_{PFN}\%$ terms than $(V_{PFN}\%)^2$ term. From both Equation 1 and 2, it appears that the $(V_{IC}\%)^2$, $V_{IC}\%$ and $V_{PFN}\%$ terms have more effects on the $\dot{D}\%$ and *Energy %*.

Discussion

In this study, it is important to note that all of the data were acquired from a single HT unit and therefore the absolute values of the AOM settings may differ from other users' HT units. Being cognizant of this, the data shown presented relative to the baseline values of the specific HT unit with the understanding that the absolute setting value will differ, however the HT units should behave in a similar fashion. Thus, the findings shown in the various figures may have a general application to most HT units.

Both V_{PFN} and V_{IC} values were shown to have effects on the HT output and energy. The V_{PFN} value shows less of a dependency on beam energy than does the V_{IC} value. Although both values must be balanced in order to keep the system in an optimized status without extreme V_{PFN} and V_{IC} value settings.

This experiment was completed in two weeks. After the AOM parameter changes were made, the HT unit was set back to the original V_{PFN} and V_{IC} values and measurements were taken to ensure the unit was back to the tolerance of baseline status. During the two weeks, the output and energy deviations were within ±2% based on daily morning quality assurance results.

Conclusion

In this study, several working zones based on the V_{PFN} and V_{IC} parameter setting were found to exist for a HT unit. Inside the normal dose rate zone, the output and energy vary linearly with V_{IC} and V_{PFN} parameter values. The results of this study may provide a quick guide for physicists to adjust their HT unit V_{PFN} and V_{IC} values in order to reset the radiation beam output and energy back to within the tolerance of the commissioned baseline.

Acknowledgements

The authors would like to thank TomoTherapy, Inc. for providing the TQA^{TM} prototype for the study.

References

1. Balog J, Holmes T, Vaden R. A helical tomotherapy dynamic quality assurance. Med Phys 2006; 33: 3939-3950.
2. Fenwick JD, Tome WA, Jaradat HA et al. Quality assurance of a helical tomotherapy machine. Phys Med Biol 2004; 49: 2933-2953.
3. Karzmark C, Nunan C, Tanabe E (Eds). Medical electron accelerators. McGraw-Hill Companies, Health Professions Divisions, 1992.
4. Langen KM, Meeks SL, Poole DO et al. Evaluation of a diode array for QA measurements on a helical tomotherapy unit. Med Phys 2005; 32: 3424-3430.
5. Mackie TR, Holmes T, Swerdloff S et al. TomoTherapy: A new concept for the delivery of dynamic conformal radiotherapy. Med Phys 1993; 20: 1709-1719.
6. Mahan SL, Chase DJ, Ramsey CR. Output and energy fluctuations of the tomotherapy Hi-Art helical tomotherapy system. Med Phys 2004; 31: 2119-2120.
7. McNiven A, Kron T. Interpolation and extrapolation of dose measurements with different detector sizes to improve the spatial resolution of radiotherapy dosimetry as demonstrated for helical tomotherapy. Phys Med Biol 2004; 49: 3665-3674.
8. Ramsey CR, Seibert R, Mahan SL, Desai D, Chase D. Out-of-field dosimetry measurements for a helical tomotherapy system. J Appl Clin Med Physics 2006; 7: 3.
9. Sarkar V, Lin L, Shi C, Papanikolaou N. Quality assurance of the multileaf collimator with helical tomotherapy: design and implementation. Med Phys 2007; 34: 2949-2956.
10. Tomotherapy I. AOM tuning guide. T-SVC-00124, Rev. A 2008.
11. Tomotherapy I. Tomo QA Guide. Tomotherapy Inc, 2007.
12. Yan Y, Papanikolaou N, Weng X, Penagaricano J, Ratanatharathorn V. Fast radiographic film calibration procedure for helical tomotherapy intensity modulated radiation therapy dose verification. Med Phys 2005; 32: 1566-1570.