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Short communications and technical notes

Operational consistency of medical linear accelerators manufactured and commissioned in series

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ABSTRACT

The purpose of this study was to determine if medical linear accelerators (linac) produced by the same manufacturer exhibit operational consistency within their subsystems and components. Two linacs that were commissioned together and installed at the same facility were monitored. Each machine delivered a daily robust quality assurance (QA) irradiation. Linacs and their components operate consistently, but have different operational parameter levels even when produced by the same manufacturer and commissioned in series. These findings have implications on the feasibility of true clinical beam matching.

Introduction

A medical linear accelerator (linac) requires meticulous checks of internal components to ensure that its output is consistent for daily operation. Internal components are subjected to various tests to ensure that they are consistent. Linacs built by the same manufacturer should be similar both internally and externally: internal components behave in a similar fashion and external radiation output measurements yield the same desired result. The purpose of this study was to determine if linacs produced by the same manufacturer exhibit operational consistency within their subsystems and components. Operational consistency facilitates detection of performance changes. Establishing universal operating parameter standards should allow for more efficient and uniform linac commissioning and maintenance processes. We hypothesize that linacs of the same model that operate with similar performance characteristics will have similar and consistent subsystem parameters.

Methods and materials

Linac performance testing

Two linacs produced by the same manufacturer that were commissioned in series and installed at the same facility were monitored. Each machine delivered a daily robust quality assurance (QA) irradiation designed to assess the interplay between gantry angle, multi-leaf collimator (MLC) position, and fluence delivery in a single delivery [1]. The QA irradiation consisted of delivering dose at narrow angular sectors by maximum gantry acceleration and deceleration. In turn, MLC position could be analyzed due to the delayed displacement of the MLC gap from one position to the other before coming to an abrupt halt at the moment of delivery [1]. Each QA irradiation generated trajectory and text log files that were used to monitor various operational components and subsystem performance. The resulting log files from the irradiation were transferred, decoded, analyzed, regrouped, and subjected to Statistical Process Control (SPC) analytics [2–8]. All computer code was written in MATLAB (Mathworks, Inc. Natick, MA, USA) [9]. The QA irradiation delivery parameters reported here are representative of the 525 performance parameters being monitored.

The performance parameters investigated belong to two major subsystems: beam generation and monitoring (BGM) and motion control (gantry, collimator, MLC, etc.). The BGM subsystem is

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responsible for setting the operating values for beam generation components. Motion control subsystems control the movements of the machine and consist of the various motion axes that move the machine and support the delivery of the beam [10–13].

The BGM subsystem consists of a central controller board and five subnode boards. The central controller board monitors all beam functions to ensure that the beam remains within manufacturer tolerance [14–16]. The board will interlock the linac when the beam is outside of these limits [10–13]. The BGM-Pulse Width Modulation (PWM) subnode controls the coils that steer the beam [10–13,17]. Thus, differences in performance parameters in this subnode can show that linacs deliver a similar beam at varying operational performance values. Performance parameters within each subnode of the BGM subsystem were investigated in greater detail to determine how differently they performed within each linac.

Subsystem motion is controlled through the Supervisor (SPV) by motors that drive motion axes and sensors that provide feedback [10–13]. Based on information from the treatment plan, the SPV determines the required positions of each of the axes and the dose to be delivered. The SPV then sends commands for all motions to the nodes for each of the axes. If the SPV does not receive a feedback reply from the nodes or the nodes do not receive instructions from the SPV, the subsystem issues a communication fault interlock, and stops the treatment [15–17].

Statistical testing

SPC analytics consisted of calculating the individual grand mean, moving range and grand mean (I/MR) chart values. They were determined as follows:

$$\bar{I} = \sum_{t=1\ldots T} I_t/T \tag{1}$$

$$MR_t = |I_t - I_{t+1}| \tag{2}$$

$$\overline{MR} = \left[\sum_{t=1\ldots T-1} MR_t\right]/(T-1) \tag{3}$$

where $T = 20$, I_t is the individual value of the performance parameter, and MR is the moving range. Control chart limits were calculated as follows:

$$3_{\sigma(\bar{I})} = [(\pm(3/d_2)\overline{MR})] \tag{4}$$

$$UCL_I = \bar{I} + [((3/d_2)\overline{MR})] \tag{5}$$

$$LCL_I = \bar{I} - [((3/d_2)\overline{MR})] \tag{6}$$

where d_2 is a normality constant that is dependent upon the sample size.

Each operating performance parameter was subjected to a ranked analysis of variance (ANOVA) to determine if there were differences between each of their parameter means [18]. The distributions of the outcomes were analyzed and due to outliers we used non-parametric approaches for the analysis. The use of non-parametric methods is needed due to data outliers having a non-normal distribution. We believe the statistical approach used is correct due to the highly skewed distributions in the data and do not believe these are due to error in measurement. A ranked ANOVA was performed because each accelerator had an unequal amount of QA irradiation deliveries. Each original data point value is ranked from 1 for the smallest to N for the largest. Ranking improves the data set by adding robustness to non-normal errors (due to unequal sample sizes) and resistance to outliers [18]. Parameters were also graphically compared using their parameter medians and performance operating window. The median is reported because it is a better measure of centrality than the mean when outliers are present [4–6,8]. The "range" is the minimum and maximum median of a parameter.

To depict the differences, the medians of the "I" chart values were plotted for each performance parameter within each subnode. Another visual investigation to further test this theory was examining how each performance parameter deviated from its overall median value. This interpretation provides a method of determining whether a performance parameter operates at a single, specific value. An overall median value was determined for each performance parameter in each subnode for each linac. A final investigation used the calculated limits of each performance parameter. This procedure depicts the operating window in which the parameter is performing for each linac [3–8,19–23].

Results

As detailed in the subsections below, linacs produced by the same manufacturer and commissioned in series were found to be statistically and operationally different (p-value < 0.00001). Each monitored performance parameter was statistically different and operated at a unique, distinct value. Yet, each linac met clinical treatment performance specifications as recommended by TG-142 with no output changes observed during the monitoring process.

Beam generation and monitoring

Table 1 shows performance parameters contained within the BGM-PWM subnode. It is representative of all subnodes and their respective performance parameters contained within the BGM subsystem. The results of the ranked ANOVA indicate that performance parameters monitored within each subnode of the BGM subsystem were statistically different between linacs (p-value < 0.00001). The initial results indicate that each performance parameter operate collectively at a distinct and consistent value.

It was visually determined that for each performance parameter, each linac had distinct median values (Fig. 1). Performance parameters related to beam symmetry or flatness in the radial and transverse planes had median values that were consistently different (Fig. 1a). The median values in the Position coils were larger than those in the Buncher and Angle steering coils. Each parameter had a unique operating window characteristic of that particular linac; i.e., there was minimal overlap when comparing against each other (Fig. 1b). Thus, linacs and their components operate consistently but perform at different operational values even when produced by the same manufacturer and commissioned in series.

Motion control

Table 2 reports the important linac delivery parameters contained within the motion control subsystem. The results of the ranked ANOVA indicate that performance parameters monitored

Table 1
Statistics for BGM-PWM performance parameters in two linacs.

Performance parameter	Range	P-value
Buncher Radial Current (A) – BRC	−0.110 to 0.125	<0.00001
Buncher Transverse Current (A) – BTC	0.065 to 0.115	<0.00001
Angle Radial Current (A) – ARC	−0.064 to 0.006	<0.00001
Angle Transverse Current (A) – ATC	−0.007 to 0.011	<0.00001
Position Radial Current (A) – PRC	−0.847 to 0.273	<0.00001
Position Transverse Current (A) – PTC	0.296 to 0.759	<0.00001