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Verification of a novel method for tube voltage constancy measurement of orthovoltage x-ray irradiators

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Purpose: For orthovoltage x-ray irradiators, the tube voltage is one of the most fundamental system parameters as this directly relates to the dosimetry in radiation biology studies; however, to the best of our knowledge, there is no commercial portable quality assurance (QA) tool to directly test the constancy of the tube voltage greater than 160 kV. The purpose of this study is to establish the Beam Quality Index (BQI), a quantity strongly correlated to the tube voltage, as an alternative parameter for the verification of the tube voltage as part of the QA program of orthovoltage x-ray irradiators.
Methods: A multipurpose QA meter and its associated data acquisition software were used to customize the measurement parameters to measure the BQI and collect its time-plot. BQI measurements were performed at 320 kV with four filtration levels on three orthovoltage x-ray irradiators of the same model, one of which had been recently energy-calibrated at the factory.
Results: For each of the four filtration levels, the measured BQI values were in good agreement (<5%) between the three irradiators. BQI showed filtration-specificity, possibly due to the difference in beam quality.
Conclusions: The BQI has been verified as a feasible alternative for monitoring the constancy of the tube voltage for orthovoltage irradiators. The time-plot of BQI offers information on the behavior of beam energy at different phases of the irradiation time line. In addition, this would provide power supply performance characteristics from initial ramp-up to plateau, and finally, the sharp drop-off at the end of the exposure.
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Key words: x-ray tube voltage constancy, orthovoltage irradiator quality assurance

1. INTRODUCTION

The constancy of the tube voltage is one of the key components in the quality assurance (QA) program of a biological x-ray irradiator, in order to ensure reproducible dose delivery in radiobiological research—simply put, that the kV reading on the irradiator control panel must be consistent with that of the actual x-ray beam. In the United States, orthovoltage (200–500 kV by definition) x-ray irradiators have become one of the main alternatives for the traditional Cs-137 gamma-ray (662 keV) irradiators in radiobiological research; this was in part due to Homeland Security concerns associated with a high-activity Cs-137 source.[1] Due to the lower average energy, photoelectric interaction has an increased role in orthovoltage irradiators as compared to in Cs-137 irradiators. This adds to the importance of tube voltage constancy in the perspective of QA, as small deviations from the tube voltage setting could potentially result in a significant change in the energy deposition mechanism in the irradiation subject, i.e., cells or organisms.

Unfortunately, tube voltage constancy measurement for orthovoltage x-ray irradiators can still be a challenge in practice. The traditional method for the kV constancy test for orthovoltage x rays is to use a voltage divider; this is, however, not generally available in the radiobiology laboratory settings. Today's diagnostic medical x-ray QA instruments uses a different method, the principle of which is that the tube voltage is correlated to the dose ratio of the same x-ray beam passing through different attenuators.[2–4] Instruments using this method for tube voltage measurement employs a pair of matched detectors filtered by different attenuators. The ratio of the detector response from both detectors depends on the beam quality (energy spectrum) of the x-ray beam; hence, a tube voltage value can be reported by matching the ratio to a calibration look-up table in the instrument. However, these commercial QA products are not calibrated to measure the tube voltage beyond the diagnostic kilovoltage range, i.e., >160 kV.[5,6] The purpose of this study is to verify the feasibility of using the Beam Quality Index (BQI), a dose ratio quantity used in a commercial diagnostic QA meter's customized measurements, as an alternative parameter for tube voltage constancy measurements for orthovoltage x-ray irradiators. The BQI is given by

$$\text{Beam Quality Index (BQI)} = \frac{D_A}{D_B}, \quad (1)$$

where D_A and D_B are the detector response for the same x-ray beam after passing through attenuators A and B, respectively.

2. METHODS

2.A. Orthovoltage x-ray irradiators

Three orthovoltage x-ray irradiators were used (X-Rad 320, Precision X-ray, North Branford, CT) for measurements. Each of these irradiators employs an x-ray tube that consists of a tungsten anode of 30° target angle and an inherent filtration of 3 mm beryllium.

Irradiator #1 located at the Precision X-ray facility, was recently energy-calibrated with a voltmeter and the irradiator's built-in high-voltage divider in the circuitry, and served as our gold standard. Two other irradiators (#2 and #3) are located at Duke University.

2.B. Measurement of BQI

Measurements were performed using a multipurpose QA meter (Meter Model: Piranha; RTI Electronics AB, Mölndal, Sweden) and its associated data acquisition software (Ocean Professional, v2013.01.14.85; Electronics AB, Mölndal, Sweden). The BQI was the detector response ratio after two beam attenuators (2 mm silver and 0.5 mm brass) in the QA meter. BQI measurements on Irradiators #1 and #2 were performed from 80 to 320 kV, in 20 kV intervals, with four filtration levels: No filter; Filter A (2 mm Al); Filter B (0.8 mm Sn + 0.25 mm Cu + 1.5 mm Al); and Filter C (0.1 mm Cu + 2.5 mm Al). BQI measurements on Irradiator #3 were performed from 100 to 320 kV, in 20 kV intervals, with only Filter A. For each irradiation session, the BQI was tracked for the first 8 s, with 250 samples per second.

3. RESULTS

BQI measurements are shown in Fig. 1 below. At each filtration level, a fourth-order polynomial is used to fit the BQI data points of Irradiator #1. Good agreement in BQI (<5%) were observed between Irradiator #1, the gold standard, and Irradiators #2 and #3. Across different filtrations levels, the BQI values for No Filter, Filter A, and Filter C were within 10% each other at each kV level; the much higher BQI values for Filter B were most likely the result of significantly hardened beam spectra. At 320 kV, the mean energies of the x-ray tube with Filters A, B, and C are 85, 150, and 94 keV, respectively, based on simulations by GEANT4 (v9.402) of the x-ray tube.[7]

BQI time-plots (sample plots shown in Fig. 2) demonstrate the BQI, and hence the tube voltage, ramp-up at the beginning

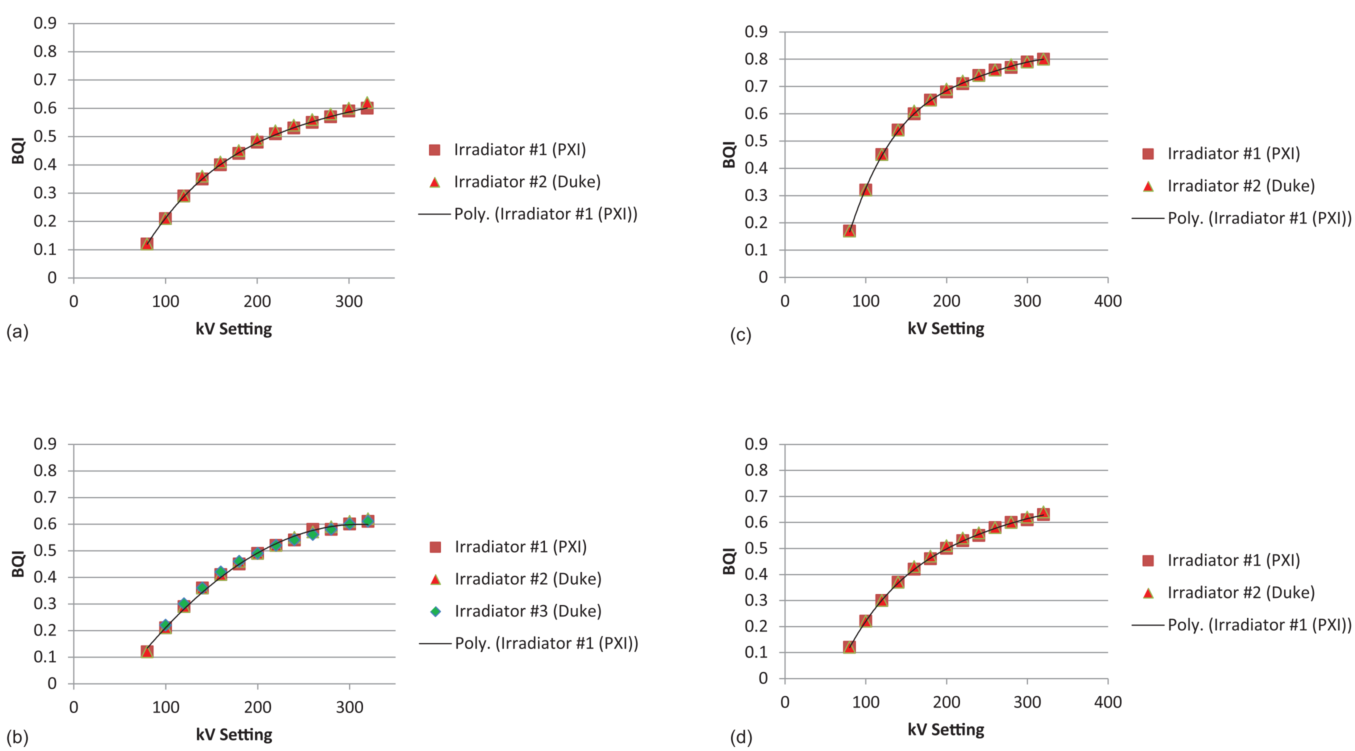

FIG. 1. Measured BQI at the three X-Rad 320 Irradiators at various filtration levels: (a) No filter; (b) Filter A; (c) Filter B; and (d) Filter C.

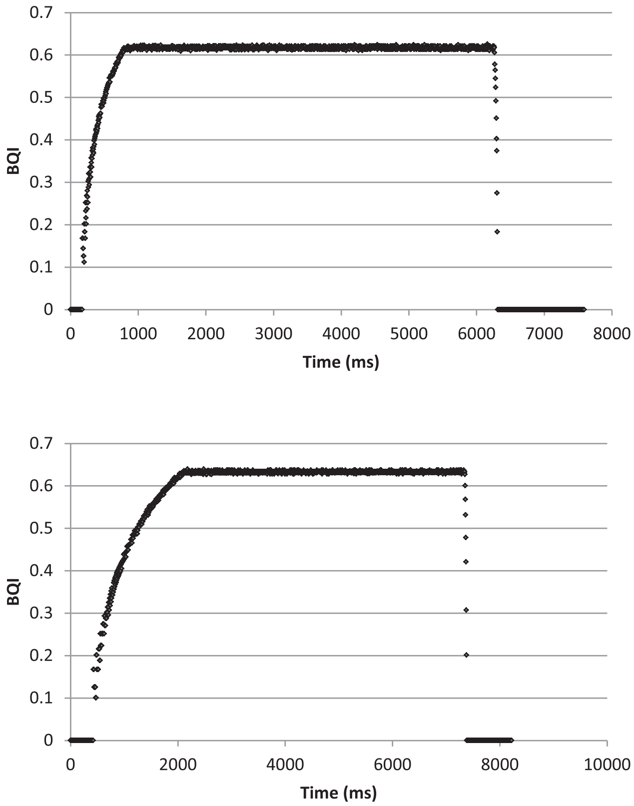

FIG. 2. Sample BQI time-plots (Top: Irradiator #1, Filter A, 320 kV, 5 s irradiation; Bottom: Irradiator #2, Filter A, 320 kV, 5 s).

of exposure, plateau-region during exposure, and the sharp drop-off at the end of exposure. Different ramp-up times were due to the different ramp-up settings in the power supply units of the irradiators.

In the absence of any direct tube voltage verification capability, the BQI-kV fit curve can potentially serve as an alternative method for kV constancy. Spectrum-specificity has been observed with different filtrations, more significant with the Filter B. Therefore, as part of an irradiator QA program, the tube voltage monitoring can be done by measuring the BQI and comparing it to a reference BQI-kV calibration curve for the x-ray spectrum of interest. In addition, the time-plot of BQI offers information on the behavior of beam energy at different phases of the irradiation, which is potentially valuable for monitoring the power supply stability as well as the timer error correction in radiation dosimetry.

Despite the extensive use of irradiators in radiobiological research, there is still room for improvement in the area of physics support. As Yoshizumi *et al.*[8] have reported, "Physics support is needed, but is often the weakest link in the small animal dosimetry chain." The current status of irradiator physics, especially orthovoltage x-ray units, calls for more recognition of the importance of having a rigorous irradiator QA program and advancement in related technological and scientific research. Specifically for the topic of this study, the monitoring of the tube voltage bears long-term future benefit since the stability of the irradiator power supply system may likely become an issue due to system aging and usage.

As mentioned in the Introduction, common commercial x-ray QA instruments, including the one employed in this study, the Piranha by RTI Electronics AB without measurement customization, are not calibrated to directly report tube voltage beyond 160 kV, mainly because the target market for such products are usually the clinical diagnostic x-ray units, instead of orthovoltage units for biological irradiations. Our study shows that, with proper measurement customization, the BQI, a measured quantity used internally in the Piranha, can serve as an alternative output quantity for tube voltage constancy. In the future, we are interested to investigate if similar products by other manufacturers can be customized and employed to achieve the same goal. For any of these products, often the key is whether the firmware within the detector allows for such customized measurements to go beyond 160 kV; we were fortunate that the associated software of the Piranha had this capability.

Our approach basically verified that, in the absence of direct kV constancy measurement, BQI constancy measurements can be performed on 320 kV x-ray irradiators. This approach can be used for other orthovoltage x-ray units as long as the BQI is always compared to previous measurements of the same irradiations protocols of the same device. Our method fills a current technological void in tube voltage validation and monitoring for orthovoltage irradiators. In addition, the BQI time-plots acquired provide useful information about the irradiator power supply performance characteristics from initial ramp-up to plateau, and finally, the sharp drop-off at the end of the exposure.

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