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Fabrication of applicator system of miniature X-ray tube based on carbon nanotubes for a skin cancer therapy

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1. Introduction

A miniature X-ray tube is a small X-ray generation device generally with a diameter of less than 10 mm [1-5]. Because of the feasible installation in a spatially constrained area and the possibility of electrical on/off control, miniature X-ray tubes can be widely used for nondestructive X-ray radiography, handheld X-ray spectrometers [1,2], electric brachytherapy, and interstitial or intracavitary radiation therapy or imaging with the substitution of radioactive isotopes [3-5]. Miniature X-ray tubes have been developed mostly using thermionic electron sources [3,4] or secondary X-ray emission [5].

In addition, X-ray tubes based on carbon nanotube (CNT) field-emission electron sources have been extensively developed because CNT emitters have several advantages compared with thermionic electron sources. The advantages of CNT emitters include (1) cold electron sources, and hence, little heat is generated inside the tube [6] which is important for the minimization of an X-ray tube; (2) simplicity and easy controllability in a pulse operation [7,8]; (3) high current density for electron and X-ray microscopy devices [9,10]. Several types of X-ray tubes have also been developed using CNT field emitters [11-15].

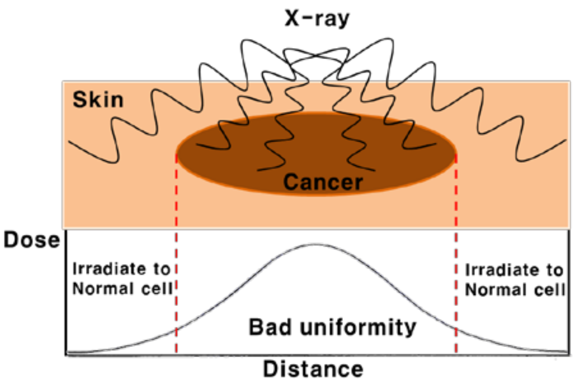

Figure 1. A schematic of the skin cancer therapy using non-uniform X-ray dose distribution.

Meanwhile, when miniature X-ray tubes are used for a skin cancer therapy, a X-ray dose uniformity is important factor for the treatment. Actually the X-ray dose distribution of conventional X-ray tubes is not uniform that had just Gaussian shaped distribution. If a non-uniform X-ray was irradiated to a skin cancer on a patient, some cell parts of the skin cancer can be irradiated excessively or healthy cells can be also damaged. Therefore, the uniformity of X-ray dose distribution should be obtained for the skin cancer therapy.

2. Methods

The fabrication processes of miniature X-ray tubes and applicators for the skin cancer therapy are schematically displayed in Figure 2. The X-ray tube has a diode structure, which consists of a CNT cathode tip and a focusing electrode on one side and a conical-shaped transmission-type X-ray target on the other side. An alumina ceramic tube (inner diameter 5 mm, outer diameter 7 mm) is used for the high-voltage insulation between the cathode and the X-ray target. The X-ray target was fabricated by coating W on a conically machined beryllium (Be) X-ray window using a magnetron sputter. The thickness of the coated W film is 1.5 μm, which is optimized to produce a maximum X-ray output for a given electron beam input [16].

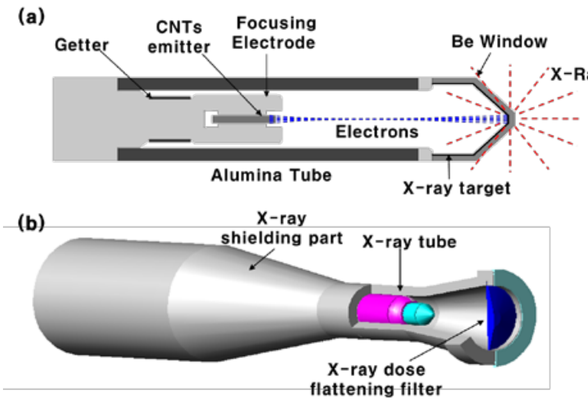

Figure 2. Schematics of (a) a vacuum-sealed miniature X-ray tube based on a CNT field emitter and (b) applicator system for the skin cancer therapy, respectively.

All of the connection parts of the X-ray tube are tightly vacuum-sealed. The both ends of the alumina ceramic tube were vacuum-brazed with a focusing electrode assembly and a connecting anode, respectively. Both electrodes were made of Kovar (Carpenter Technology Corporation, Reading, PA, USA) that has a similar thermal expansion coefficient to alumina. The connecting anode was used to interconnect a ceramic tube and a Be X-ray window that have different thermal expansion coefficients. The connecting anode and the Be window were also vacuum-brazed. All the components of the X-ray tube were baked at 550°C for 24 h, and subsequently, these were brazed through a single-step brazing process at 700°C for 15 min in a vacuum furnace. Before the brazing process, electron emission and transport tests of the X-ray tube have been carried out inside a vacuum chamber.

3. Results and discussion

Figure 3a shows an optical image of the fabricated X-ray tube. The diameter of the X-ray tube is 7 mm and total length is 47 mm. Figure 3b exhibits typical field emission characteristics of the fabricated X-ray tube. The cathode and the focusing electrode of fabricated miniature X-ray tube were floated in negatively high voltage while the X-ray target was grounded. X-ray tube current of 265 ㎂ was achieved at the tube voltage of 50 kV. The fabricated miniature X-ray tube operated stably up to 70kV tube voltage.

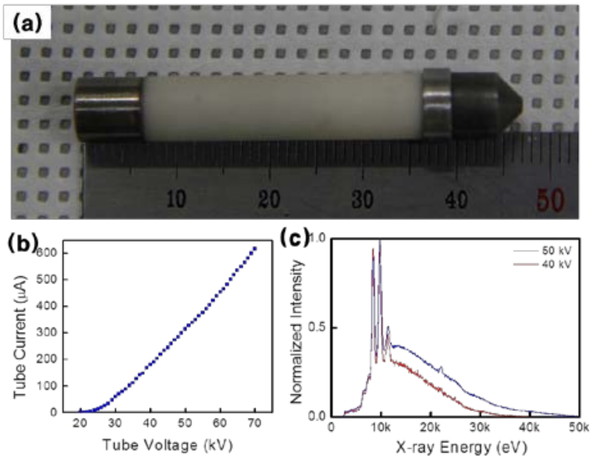

Figure 3. (a) An optical image of the fabricated X-ray tube. (b) field emission property and (c) X-ray spectrum of the miniature X-ray tube, respectively.

Figure 3c displays the energy spectrum of the X-rays generated from the miniature X-ray tube operating at 50 kV. The spectrum was measured with an X-ray spectrometer (Amptek XR-100 T-CdTe, Amptek Inc., Bedford, MA, USA). The spectrum includes broad bremsstrahlung X-rays with energies of up to 50 keV and a few characteristic X-rays at 8.4, 9.7, and 11.3 keV that respectively correspond to $L\alpha1$, $L\beta1$, and $L\gamma$ 1 of the W target.

Furthermore, a spatial X-ray uniformity generated by the fabricated X-ray tube was measured for a skin cancer therapy (Figure 4). Figure 4a exhibits a film dosimetry irradiated by the X-ray tube without a flattening filter. A non-uniformed X-ray distribution was obtained and the uniformity of the X-ray tube without the flattening filter had a higher than 20%. However, when an optimized flattening filter was installed with the applicator system of the miniature X-ray tube, a spatial X-ray dose uniformity was remarkably improved as shown in Figure 4b. The irradiated part of scanned image (red circle) in the Gafchromic film (the inset of Figur 4b) shows an identical color, which means that all irradiated areas were exposed by almost same amount of X-ray dose. As a result, the uniformity obtained by the X-ray tube with the optimized flattening filer was a lower than 10 %.

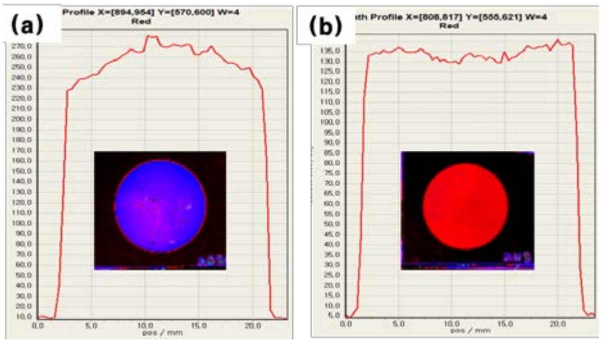

Figure 4. Spatial X-ray uniformities of the fabricated X-ray tubes (a) without and (b) with the flattening filter, respectively. Insets: Scanned images of the irradiated Gafchromic films.

4. Conclusions

Miniature X-ray tube based on carbon nanotubes was fabricated after design. The X-ray tube show excellent field emission properties and good X-ray spectrum. Also, the flattening filter was made to irradiate uniformly. The X-ray dose radial uniformities between installed flattening filter and non-installed flattening filter were measured. When flattening filter is equipped, X-ray uniformity was improved from higher than 20% to lower than 10%. As a result, the fabricated applicator system of the miniature X-ray tube using optimized flattening filter exhibited fairly excellent properties.

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