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Original Article

An Intraoral Miniature X-ray Tube Based on Carbon Nanotubes for Dental Radiography

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ABSTRACT

A miniature X-ray tube based on a carbon-nanotube electron emitter has been employed for the application to a dental radiography. The miniature X-ray tube has an outer diameter of 7 mm and a length of 47 mm. The miniature X-ray tube is operated in a negative high-voltage mode in which the X-ray target is electrically grounded. In addition, X-rays are generated only to the teeth directions using a collimator while X-rays generated to other directions are shielded. Hence, the X-ray tube can be safely inserted into a human mouth. Using the intra-oral X-ray tube, a dental radiography is demonstrated where the positions of an X-ray source and a sensor are reversed compared with a conventional dental radiography system. X-ray images of five neighboring teeth are obtained and, furthermore, both left and right molar images are achieved by a single X-ray shot of the miniature X-ray tube.

1. Introduction

X-rays are widely used for dental imaging to diagnose dental structures, bone loss, and cavities. There are three main types of dental X-ray system: radiography, panorama, and computed tomography [1]. Dental radiography is popularly used to investigate the status of teeth and gums because it provides higher quality X-ray images with lower X-ray doses than dental panorama and computed tomography systems [2–6]. However, in current dental radiography systems, X-rays are irradiated from an X-ray tube outside the mouth next to teeth, while another X-ray sensor is placed inside the mouth (Fig. 1A). As a consequence, small-sized X-ray sensors are needed for insertion into the mouth and, thereby, the number of teeth that can be radiographically imaged is limited. Normally, images of two whole teeth are obtained by a single X-ray shot with the current dental radiography system that employs an intra-oral sensor (an X-ray sensor placed inside the mouth) and an extra-oral X-ray tube (an X-ray tube placed outside the mouth) [1,7]. Moreover, at least two X-ray shots are required to get images of teeth from both sides of the mouth.

In order to overcome the disadvantages of conventional dental radiography, a novel dental radiograph has been

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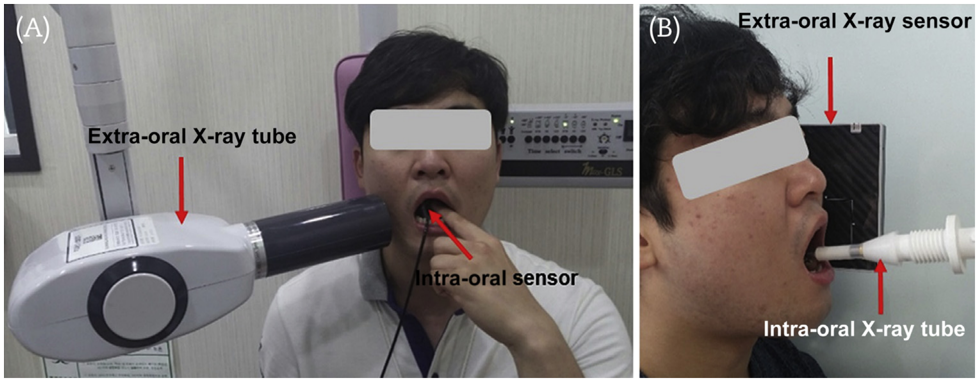

Fig. 1 – Radiography. (A) Conventional dental radiography consisting of an intra-oral sensor and an extra-oral X-ray tube. (B) A novel dental radiography based on a carbon nanotube-based intra-oral miniature X-ray tube and extra-oral X-ray sensor.

proposed in which an X-ray source is used inside the mouth while an X-ray sensor is used outside the mouth [8,9]. The intra-oral dental radiograph requires an X-ray source small enough to safely insert into the mouth (Fig. 1B). Recently, we developed a miniature X-ray tube with a diameter of 10 mm and a total length of less than 50 mm [10,11]. The miniature X-ray tube is based on a carbon nanotube (CNT) field emitter and does not require a vacuum pump for its operation. Compared with miniature X-ray tubes based on thermionic electron sources, the CNT-based miniature X-ray tube has a few advantages, including having a higher emission current, better stability, and longer lifetime [10–16]. Moreover, no cooling component is necessary in the CNT-based miniature X-ray tube because heat is not generated from a CNT electron emitter, unlike thermionic electron sources [17–19]. Furthermore, the temperature of the X-ray target can be kept low enough by operating the X-ray tube in a pulse mode. Therefore, the CNT-based miniature X-ray tube can be a good intra-oral X-ray source for the new dental radiography system. Here, we have developed a smaller CNT-based miniature X-ray tube with a diameter of 7 mm, which is a proper intra-oral X-ray source. We present a new dental radiography comprising the miniature X-ray tube and an extra-oral X-ray sensor (Fig. 1B), and show the performance of the dental radiography system. In particular, the dental radiography system was designed to enable a large number of teeth to be radiographically imaged. Furthermore, images of the teeth on both sides of the mouth are simultaneously obtained by a single X-ray shot.

2. Materials and methods

A schematic diagram of the CNT-based miniaturized X-ray tube is shown in Fig. 2A. The miniature X-ray tube has a diode structure, which consists of a CNT emitter as a cathode and an X-ray target as an anode. The CNT emitter was fabricated by attaching single-walled CNTs (model: CNT SP95, Carbon Nano-material Technology Co., Pohang, South Korea) to a 0.8-mm copper wire substrate using metal nanoparticles as a binder [20,21]. The CNT emitter was installed inside a focusing electrode, which prevents the divergence of an electron beam generated at the CNT emitter. The geometrical shape of the focusing electrode was optimized by calculating electron trajectories from the CNT emitter to the X-ray target with an EGN2 code (GA and WB Hermannsfeldt, Los Altos, CA, USA) [22]. The X-ray target has a conical-shaped transmission type. The shape of the target was designed to produce X-rays over large angles with the use of Monte Carlo N-Particle Transport code [23]. The transmission-type target was prepared by coating tungsten, at a thickness of approximately 1.5 μm, on a conical-shaped beryllium window using a magnetron sputtering device.

An alumina ceramic tube, with an inner diameter of 5 mm, an outer diameter of 7 mm, and a length of 30 mm, was used for high-voltage insulation between the cathode assembly and the X-ray target. The focusing electrode, the ceramic tube, and the X-ray target were tightly assembled in a brazing furnace. The brazing process was carried out in a vacuum at a maximum temperature of 720 °C for 5 minutes. Before the brazing process, the alumina ceramic and the focusing electrode were baked at 500 °C for 10 hours. A strip of non-evaporable getter (Model: SP122 SP Getter, SAES Group, Milan, Italy) was used to evacuate the inside of the miniature X-ray tube. It is difficult to tightly vacuum to connect the alumina ceramic and the beryllium window through brazing due to the difference in the thermal expansion coefficients of the two materials [24]. Hence, a cylindrical kovar that has a thermal expansion coefficient similar to that of alumina ceramic was inserted between the alumina ceramic tube and the X-ray target. For the same reason, the focusing electrode was also made of kovar. Fig. 2B displays all the components of the miniature X-ray tube and Fig. 2C shows the final fabricated miniaturized X-ray tube. The outer diameter of the fabricated miniature X-ray tube is 7 mm and the length of the X-ray tube is 47 mm.

The X-ray tubes were operated in a negative high-voltage mode; the cathode was applied to a negative high voltage, while the anode was electrically grounded. The cathode was connected to a commercialized high-voltage connector (model: Claymount CA3, Claymount Co., Ltd., Dinxperlo, The Netherlands). Since the X-ray tubes should be inserted into the mouth, the mouth is exposed to a high voltage, leading to a high-voltage safety issue. To protect the human body from the high voltage, the whole X-ray