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Micro Computed Tomography System Based on Field Emission X-Ray Source with Carbon Nanotube Emitter

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ABSTRACT

The properties of carbon nanotubes (CNTs) show a variety of application possibilities in the next generation industries. Among them, application to a field emission device is expected due to a high emission current at a low critical electric field. Compared with conventional thermionic emission X-ray sources, field emission X-ray sources have many advantages. Their electric field can be turned on and off quickly, minimizing radiation exposure times. Additionally, the size of the imaging system can be reduced because no cooling device is required. Using these advantages, we created a micro computed tomography (CT) system based on a CNT field emission X-ray source. The main advantages of the micro-CT lie in the high-spatial resolution, sensitivity to skeletons and lungs, and low cost. We optimized the field emission characteristics of the CNTs and the system geometry for high resolution.

Keywords: Carbon nanotube, Field emission, X-ray, Computed tomography

1. INTRODUCTION

Computed tomography (CT) is an important tool for non-invasive medical imaging, industrial detection and small animal clinicians.[1,2] The achievement of high spatial and temporal resolution in CT X-ray tubes is a major challenge. It has been demonstrated that high temporal resolution can be achieved by using carbon nanotube (CNT) based emitters. CNTs are excellent electron emitters for vacuum nano-electronic applications.[3] The key requirements of CNTs in electron emission source applications are a high emission current at a low critical electric field and stable field emission (FE) properties.[4] CNTs which are used as electron emitters in X-ray generation have excellent characteristics with a compact structure, reduced power consumption and do not necessarily require focusing electrodes. Especially, the small focal spot size of the electron beam at the anode target and the high anode current are important for producing high resolution with low dose from the X-ray source. In this paper, we demonstrate a CNT emitter-based FE X-ray system for CT imaging. The X-ray images show micrometer scale resolution with stable and repeatable measurements.

2. CARBON NONOTUBE EMITTER AND MICRO CT SYSTEM DESIGN

2.1 Fabrication of field emitter as carbon nanotube

The CNTs were synthesized using the thermal chemical vapor deposition (TCVD) method. As the substrate, a rectangular rounded metal alloy having an area of 0.137 cm^2 and width of 1.5 mm was used – [Figure 1. (a)]. First, the substrates were heated to 970°C under vacuum in a chamber. After that, C_2H_2 was inserted with NH_3 gas for 30 ~ 120 minutes with the flow rate of 30 and 70 sccm, respectively. By controlling the growth time, the density of CNTs could be controlled. Unlike conventional methods such as deposition of catalysts on patterned substrate to grow CNTs, it is possible to synthesize carbon nanotubes with very simple and excellent emission properties. Figure 1-(b) shows random growth of the CNTs, instead of the vertically aligned growth. Because the CNTs were tangled in random ways, it was difficult to measure the length accurately, but the diameter was about 40-100 nm.

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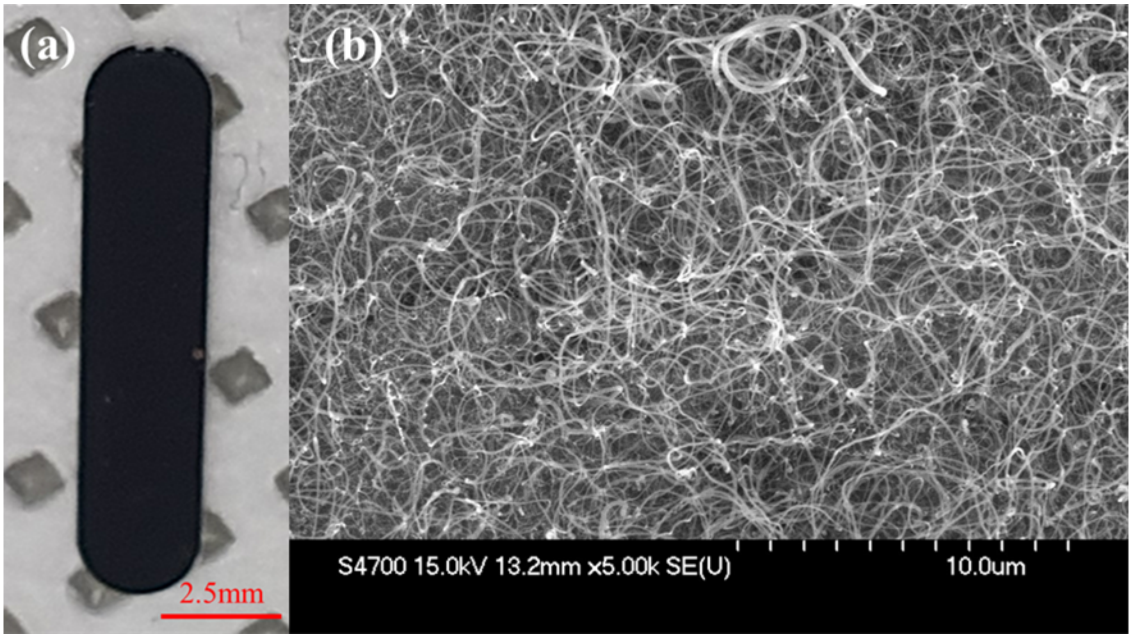

Figure 1. (a) Optical image of CNTs-grown on a metal substrate. (b) SEM image of CNT grown on substrate by TCVD.

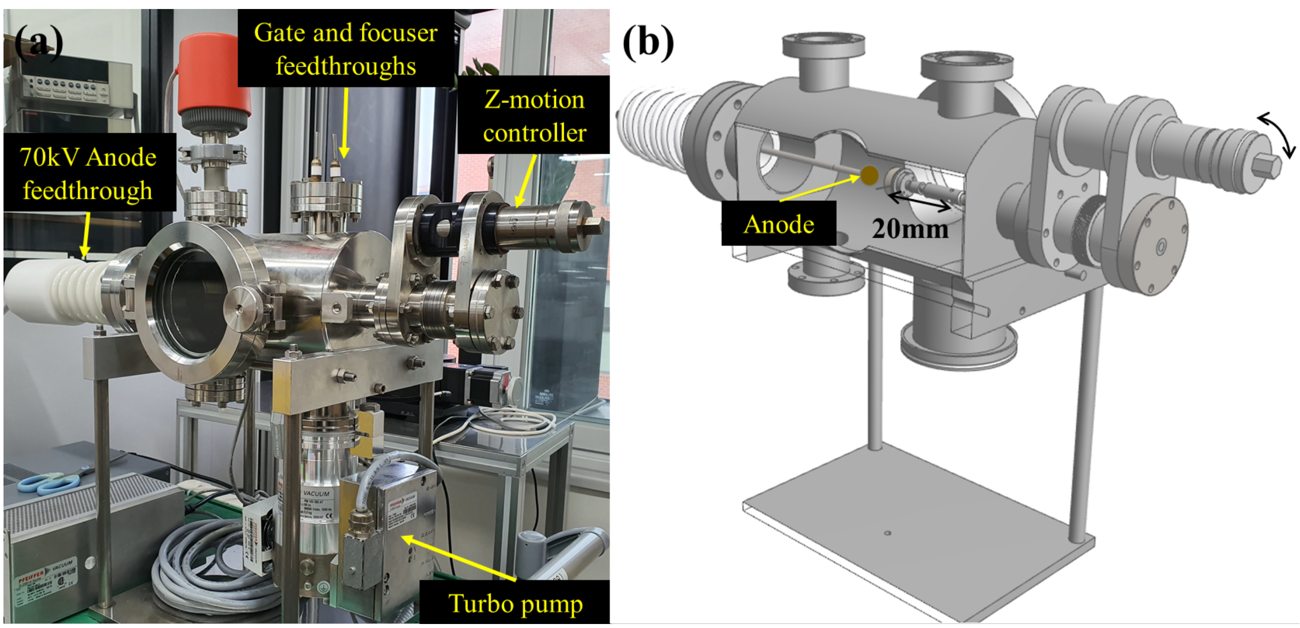

Figure 2. X-ray generating system. (a) Optical image. (b) 3D CAD image.

2.2 Micro computed tomography system design

The design of new X-ray systems using CNT cold cathodes can be a significant development in X-ray technology, leading to portable and compact X-ray sources for medical and industrial applications. Figure 2-(a) shows an optical image of the CNT based X-ray system developed herein. The system chamber was able to maintain a base vacuum of 10^{-8} Torr with by using a turbo pump. Even when 50 kV were applied to the anode causing a flow of 1 mA of field emission current, the vacuum was maintained at $\leq 10^{-7}$ Torr. Using a z-motion controller, the focal spot size can be optimized by adjusting the distance between the anode and the cathode for up to 20 mm - [Figure 2-(b)]. Figure 3 shows a schematic diagram of the micro CT system. The object is located between the X-ray source and the detector. The motor on which the object was placed can be set to steadily rotate at a constant speed. These values can be set through a customized PC program. When moving at a certain angle, the X-ray is released by applying a voltage to obtain the image and quickly turn off the power. This way, tens to hundreds of images can be obtained and unnecessary exposures can be reduced.

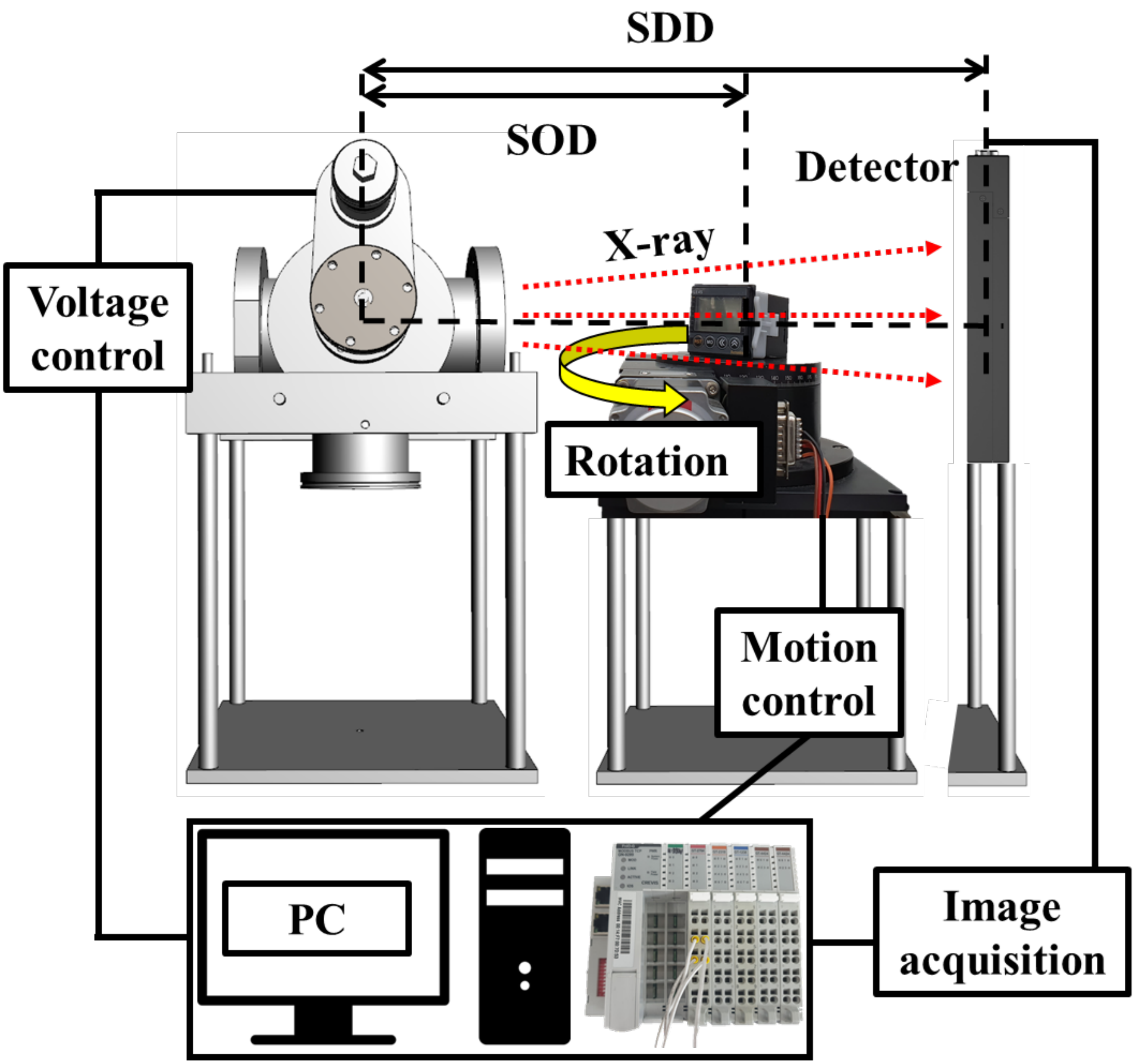

Figure 3. Schematic diagram of micro CT system.

3. DETAILED COMPONENTS OF MICRO CT SYSTEM

3.1 Design and fabrication of electron gun

Through electron beam trajectory simulation, we optimized the structure of the electron gun to minimize focal spot size. The electron gun which we employed as the X-ray source was made of ceramic, metal electrodes, an emitter cover and focuser - (Figure 4). The gate-to-CNT emitter distance was 370 µm. The CNT emitter was grounded and the electrons were extracted from the positive voltage applied to the gate electrode. When the voltage is applied to the gate electrode, electrons are emitted by field emission and the trajectory of the electron beam is controlled by the focuser. The extracted electrons are accelerated to high speeds by the high voltage applied to the anode, which is made of copper and tungsten.

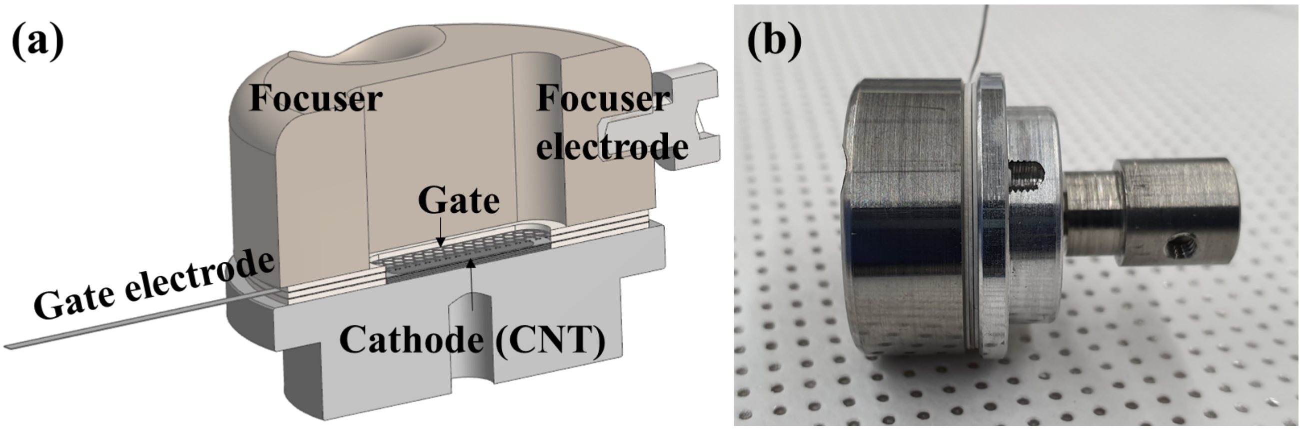

Figure 4. (a) 3D design image and (b) optical image of electron gun with CNT

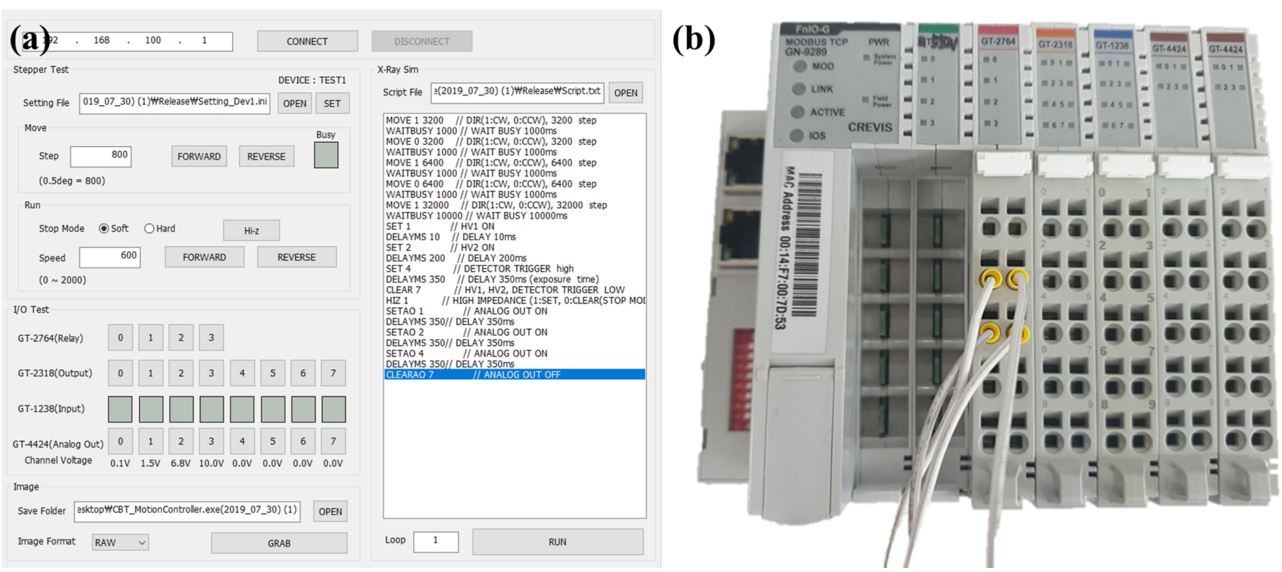

Figure 5. (a) Customized program that control the angle, rotating speed, detector and gate voltage. (b) Optical image of the module which connects the rotator, a high voltage source and the detector.

3.2 X-ray control program (motion control)

X-ray images were obtained by rotating the object to 360 degrees at 0.5-degree intervals. The scanning process was controlled by a customized program. Figure 5 shows the customized program and module which connects the rotator, a high voltage source and the detector. The program adjusts the angle and speed at which the motor moves, and turns the gate voltage on and off. It can also set up a series of steps to control the movement of the rotator and trigger the detector. Once these settings are complete, the desired images can be acquired.

3.3 Detector

We used a commercially available CMOS flat-panel detector (1215A, Rayence, Republic of Korea) with a CsI:TI scintillator as the 2D digital X-ray imager in the micro CT system. The detector has 2352 × 2944 pixels with a pixel pitch of 49.5μm, giving an active area of 116.4 × 145.7 mm^2.

4. RESULTS AND DISCUSSION

4.1 Field emission characteristics

The electrons emitted by applying a voltage to the gate electrode collide with the tungsten/copper target by acceleration due to the high voltage applied to the anode, thereby generating X-rays. The distance between the anode and the gate was maintained at 20 mm and the degree of vacuum was maintained at 10^{-7} Torr under operation. The FE characteristics are shown in Figure 6. These characteristics were measured by applying 6 kV to the anode and applying a pulse to the gate to prevent arcing from deteriorating the vacuum. When measuring current and voltage during the FE, the triode type electron gun was assembled to measure the current and voltage. The leakage current flowing to the gate during the field emission was about 17 percent of the total current.

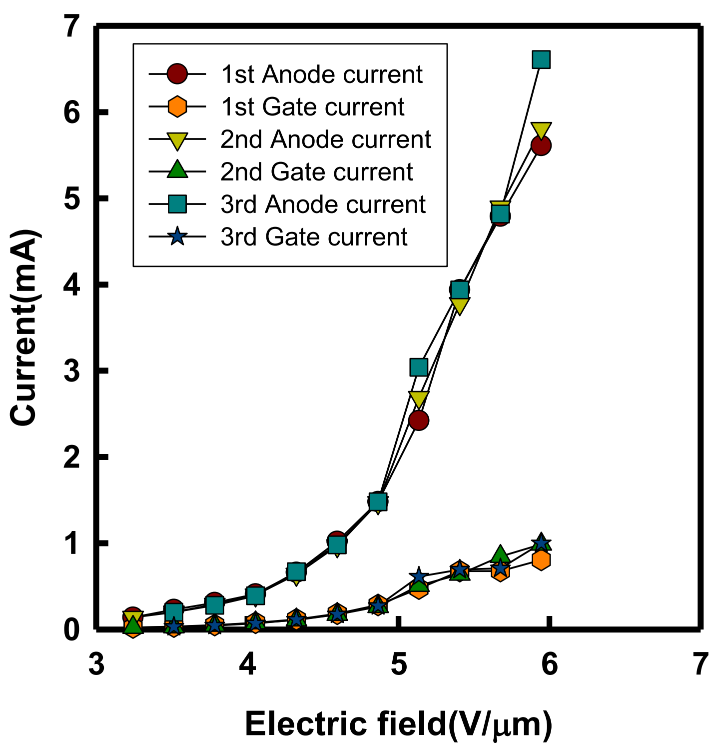

Figure 6. Field emission characteristics of under the triode configuration.

4.2 Image acquisition

Figure 7-(b-l) show X-ray images of a USB charger. The electrons were extracted from the emitter by a positive gate field 3.2 V/μm. For X-ray generation, the anode voltage and current were maintained at 50 kV and 0.5 mA, respectively, with an exposure time of 1 second. A total of 720 X-ray images were acquired by rotating the motor for one complete turn at intervals of 0.5 degrees. We can clearly see the transmitted images of the USB charger. X-ray images obtained from all angles were similar in quality.

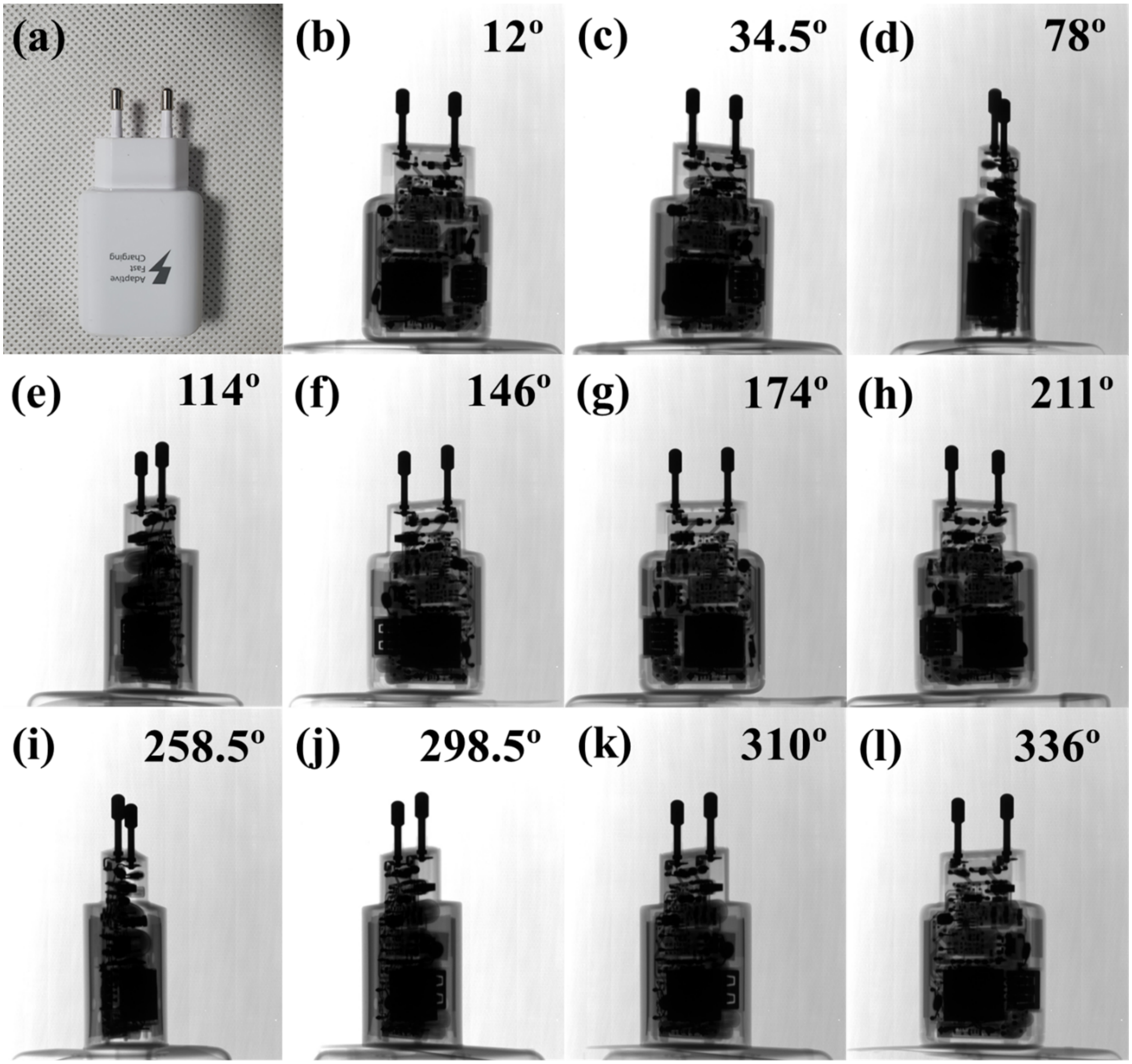

Figure 7. (a) Optical image of a USB charger. (b-l) are X-ray images the USB charger acquired at different angles by exposure for one second. The anode voltage and current were 50 kV and 0.5 mA, respectively.

5. CONCLUSION

A CNT emitter based X-ray system for micro CT was demonstrated for medical imaging. The CNT emitter based X-ray system with an object rotator was successfully constructed. By rotating the object, X-ray images of similar quality were obtained from different angles. The X-ray images were obtained at low current because the vacuum inside the chamber was unstable at high current. If this problem is solved, the X-ray exposure time can be reduced, resulting in faster acquisition of the CT images.

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