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# Tabletop high-resolution breast specimen imaging system based on field emission CNT X-ray source

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## ABSTRACT

Based on the breast imaging and reporting data system (BI-RADS) for mammography (MMG) and types of cancer cells detected, a patient is listed into various categories which determine whether they should undergo biopsy or not. Generally, patients under the BI-RADS category 4 or 5 have to go through surgery. During the surgery, a pathological examination is performed with the help of a microscope and additional X-ray images of the removed tissue or breast specimen are taken to determine the positive and negative surgical margins. Although the pathological examination is the best way to determine carcinoma at the inked margin, it consumes a significant amount of time and makes the duration of the surgery longer. In this study, we propose the open-type carbon nanotube (CNT)-based X-ray system, which can be helpful to determine the carcinoma on breast specimen during breast surgery. The technique proposed in this study successfully obtained X-ray images of a breast specimen with visibly clear cancer masses. These results could pave the way for efficient determination of surgical margins by eliminating the time-consuming histological procedures.

**Keywords:** Breast specimen imaging, open-type x-ray system, cancer cells, CNT, field emission X-ray

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## 1. INTRODUCTION

Non-palpable breast cancer with or without microcalcifications is mostly diagnosed by mammography (MMG) [1,2]. If the diagnosis falls under BI-RADS (breast imaging and reporting data system) category 4 or 5, it is considered as a suspicious lesion and biopsy or surgical excision is recommended [3]. The main treatment for the removal of malignant breast tumor is considered to be surgery [4]. Preceding the surgery, locations of malignant masses on breast tissues are confirmed through MMG. Depending on the size and distribution of the lesions, the patients usually undergo partial or complete resection of breast tissue with a rim of normal tissue around it. The reason to do so is to ensure or avoid the possible risk of local recurrences [2]. Thus, one of the main goals of surgeons during the surgery is complete removal of the lesions. During the surgery, it is important to identify the extent of the malignant tumor. If the removed breast specimen has malignant masses that are within 1 cm from its margin/boundary, then it is termed as a positive margin. A positive margin signifies that the patient should undergo breast surgery again to avoid the possible risk of local reoccurrences. If the breast specimen shows a negative margin (i.e. the cancer cells are located at least 0.1 cm far from the margin), then the surgery is considered successful and the patient does not have to undergo further surgery. After the removal of the breast tissue containing the malignant mass, the usual procedure is to determine the surgical margin through histological or pathological examination and taking X-ray images of it [1,3]. However, histological examination, though reliable, is a time-consuming procedure and both the surgeons and the patients have to wait at least 1 to 2 hours for the results to confirm whether the patient should undergo further surgery or not.

We can avoid this time-consuming process by acquiring the X-ray images of removed breast tissue through an alternative procedure that is preferably time-efficient. We propose here the use of an open type carbon nanotube (CNT)-based X-ray system [5]. Current X-ray technologies are analog and inefficient, as they are based on filament emitters.

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Filament emitter-based X-ray systems are bulky and have inefficient X-ray emissions with high radiation dosage, which necessitates the use of dedicated facilities that are strictly controlled. On the other hand, CNT-based X-ray systems are cold-cathode electron field emitters with superior properties such as compact structure, low power consumption, robustness, and active control functions. Small focal spot size, low dose, digital switching, and high-resolution are other attractive attributes of the CNT-based X-ray systems [6]. We have previously reported our design of the open type X-ray system and its performance [7]. We have been able to develop a compact field emission system that is able to generate sufficient electrons to produce X-ray images of a printed circuit board, a live mouse with cancer cells, and human teeth [7–9].

In this study, we developed a compact 2.5-inch open type CNT based X-ray system to detect the cancer cells on postoperative breast specimens. For high-resolution X-ray imaging, we develop pointed emitter sources and measure their field emission characteristics. Using the CNT emitters, X-ray images of a breast specimen are taken to detect the presence of cancer cells.

## 2. MATERIALS AND METHODS

### 2.1 Development of the 2.75 inch compact open type x-ray system

Figure 1(A) and (B) show an optical image and a 3D CAD diagram of the potable open-type x-ray system. The two opposite sides of the 2.5 inch X-ray system consist of an electrical feedthrough for the high voltage anode source on one side and a cathode/gate feedthrough on the opposite side. The remaining two sides have a viewing glass window and a molecular turbo-pump connected to an ion pump. The down side of the system is attached to a rectangular stand with four pillars and has an aluminum (Al) window. The emitted X-rays are directed downwards and the specimen is put inside a plastic bag and placed above the detector. The reflecting anode has a radius of 5.5 mm and is sliced at angle of $17^0$. The anode is made up of tungsten embedded on copper. The electron gun consists of CNT emitters grown on a metal substrate (Figure 1(C)). The gate and cathode are separated by a ceramic spacer and maintained at a distance of 370 µm. Two high voltage power sources are used separately for anode and the gate.

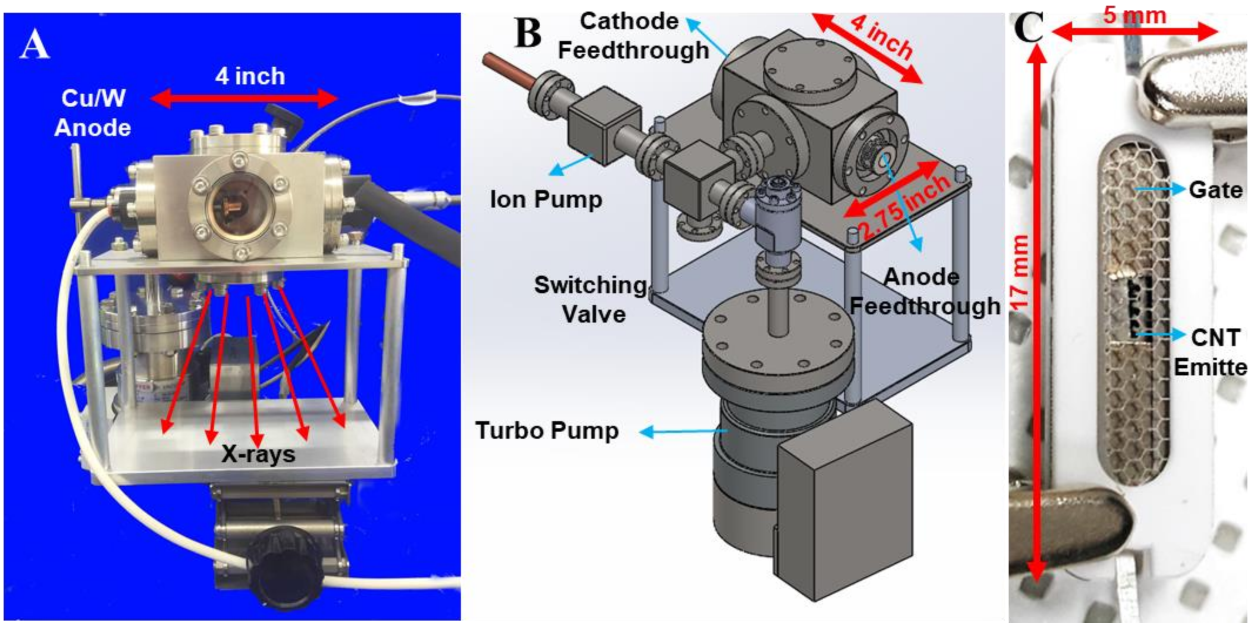


Figure 1. (A) optical image of the open type x-ray system, (B) 3D CAD diagram and (C) optical image of electron gun.

## 2.2 Development of Pointed Emitter Source

The CNTs are grown by Chemical Vapor Deposition (CVD) on a metal alloy substrate. While growing the CNTs, it is important to choose the type of substrate and pretreatment [10,11]. Growing CNTs on metal substrates is easier to process than growing on silicon substrates. Additionally, there is enhanced contact and adherence between CNTs and the metal substrates [12]. However, it is difficult to pattern the CNT-emitters and to grow them vertically. Many studies suggest that field emission properties of CNTs are strongly related to their structure and arrangement [13–15]. To solve this problem, we patterned the metal alloy substrate to create space between the emitters, which can reduce screening effect between the emitters. The patterned substrate has a number of pointed edges, thereby maximizing the effect of electron emission. Note that pointed edges produce higher field emission currents than flat surfaces.

Figure 2(A) and 2(B) show an optical microscopic image of a non-patterned and pointed substrate, respectively. The pointed substrate is developed because the electron emission from a small area (the pointed edge) helps to obtain high-resolution x-ray images. To make the pointed electron source, the pointed structures are erected manually as shown in Figure 3. Figure 3(C and D) show an example of one (single emitter) and five (five emitter) erect pointed emitters, respectively. The non-patterned and patterned substrates have emission area of 13.77 $mm^2$ (non-patterned), 0.2 $mm^2$ (five emitter) and 0.02 $mm^2$ (single emitter). Scanning electron microscopy (SEM, Hitachi S-4700) is used to analyze the morphology of the CNT forest on the metal substrate.

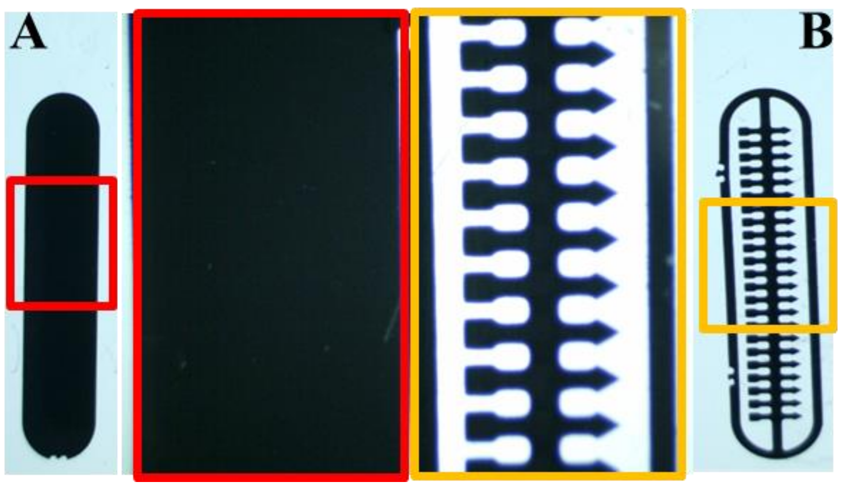


Figure 2: The optical microscopic image of (A) non-patterned substrate and (B) patterned substrate with pointed structures in the right.

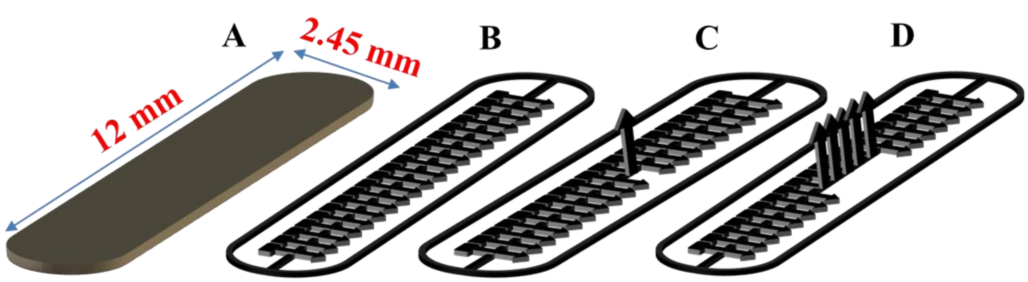


Figure 3: The schematic 3D diagram of non-patterned substrate (A), pointed patterned substrate (B), one pointed structure erected (single emitter) (C) and (D) five pointed structures erected (five emitter).

### 2.3 Obtaining of breast specimen from operation theatre

The postoperative breast specimens used in this article were obtained under the supervision of a surgeon. Before the surgery, the cancer cells or malignant masses in the breast were confirmed by the conventional mammography system. The study was performed on patients who underwent breast-conserving surgery for breast cancer in biopsy performed with suspicious calcified lesions in MMG. After partial excision, metal clipping was performed at 3 o'clock and 12 o'clock of the removed specimen to indicate the orientation of the surgical specimen. A cancerous like region on the specimen MMG was observed, and its relation with the whole breast was deduced. After the surgery, the specimen was brought to an authorized x-ray room where the proposed CNT based x-ray system was installed. The x-rays images were taken under the supervision of a radiologist and then the specimen was sent to a pathology lab for histological examination to confirm the surgical margin. Additional surgery was performed depending on the presence of the margin invasion. Frozen biopsy was performed at several sites around the cavity wall, and additional excision was determined depending on the results.

### 2.4 X-ray Image Acquisition

The x-ray image is obtained by using the triode electron gun with CNT-emitters grown on a non-patterned substrate. The anode voltage is accelerated to 30 kV with an anode current of 0.1 mA. The gate voltage is maintained at 4.3 kV with exposition time of 3 sec. As mentioned earlier, the x-ray emissions are transmitted through a downward aperture. The detector (RAD icon, 0889, Teledyne Rad-icon Imaging Corp., CA, USA) with 1024 X 512 pixels is placed 25 cm away from the Al window. The breast specimen is put inside the transparent plastic bag and is placed directly above the detector while taking x-ray images. During the X-ray emission, the turbopump is maintained at a base pressure of 4 X $10^{-8}$ Torr.

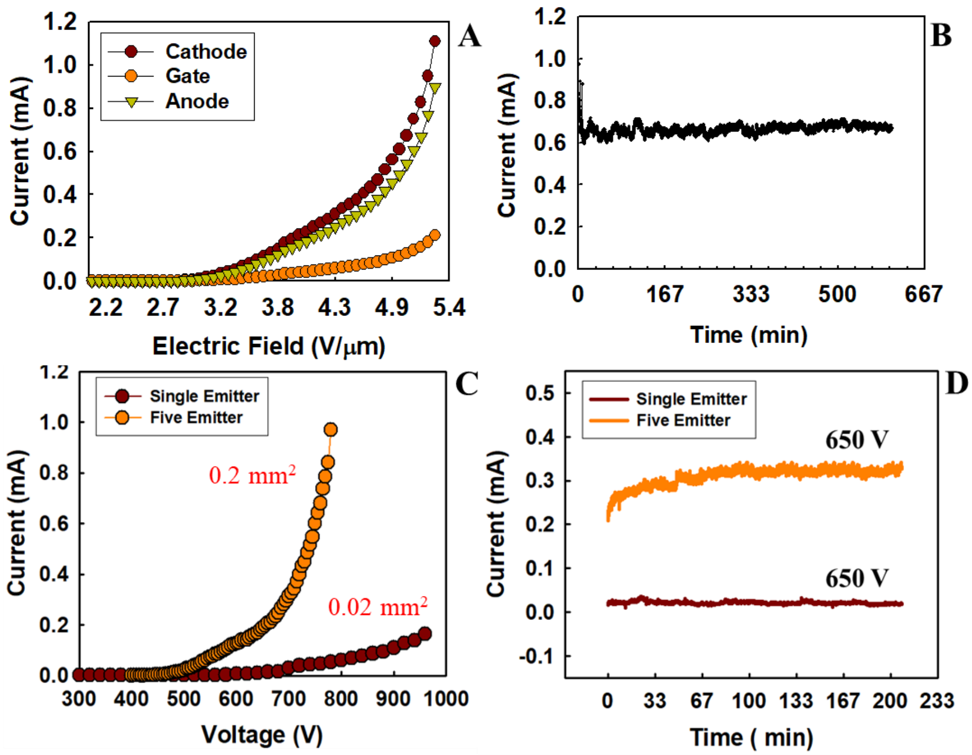


Figure 4: (A-B) Triode field emission characteristic and stability of non -patterned emitter and (C-D) field emission characteristic and stability of single and five emitter, respectively.

# 3. RESULTS AND DISCUSSION

### 3.1 Fabrication and Field Emission of CNT emitters

Figure 4(A) shows the field emission characteristic of CNT non-patterned field emitter. The cathode current of approximately 1.3 mA and anode current of 0.92 mA was obtained at a gate electric field of 5.2 V/µm. The anode current was measured by regulating the gate voltage in direct current (DC) mode. The leakage current ratio was below 20%. Figure 4(B) illustrates the stability of the CNT emitter for 630 min in DC mode. The initial cathode current was 0.9 mA at gate electric field of 5 V/µm. During the stability test, the current decreased from 0.9 mA to 0.65 mA because of the internal sparking or electrical aging process and the current remained stabled afterwards where the maximum current was 0.67 mA, and minimum current was 0.63 mA.

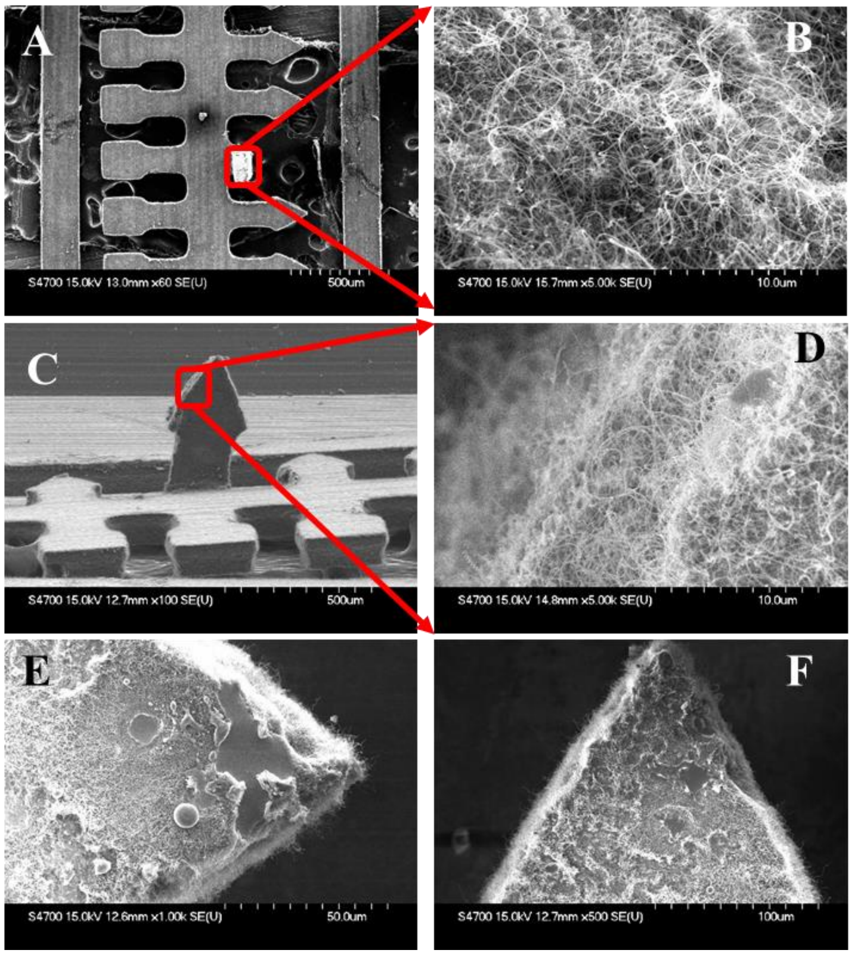


Figure 5: (A-D) CNTs on tip of pointed emitter before field emission and (E-F) melting of tip due to frequent arcing.

Figure 4(C) and (D) show the field emission characteristic and stability of the pointed emitter, respectively. The emission area for a single emitter is 0.02 $mm^2$ and that of five emitters is 0.2 $mm^2$. For the patterned pointed substrate, the field emission was carried out in a similar way. However, the gate to cathode distance changed when the pointed structures were erected. The new gate to cathode distance was 50 µm. This means that even a small increase in voltage could increase the high electric field intensity at the tip of the CNTs. The field enhancement factor is much higher for this kind of an electron gun structure and that might be the reason why the turn on voltage was very low for the five emitters. However, for the single emitter this was not the case. This is due to the fact that the emission area for a single emitter was relatively small which means that the CNTs participating in the field emission process were much fewer than five emitters. The stability test shows that both emitters were stable for more than 220 min in DC operation. The five emitters have current density as high as 500 $mA/cm^2$. This result shows that this emitter can be a perfect choice for breast specimen imaging, where low current (~300 µA) is required from the point source.

Figure 5(A-D) show CNTs grown on a pointed structure before field emission. The CNTs were densely grown and there were enough emitters at the tip for field emission. Figure 5(E-F) show the SEM images of the tip of a pointed structure after field emission. Due to frequent arcing, the substrate melted due to the high electric field at the tip of the pointed structure. This gives us the information that we might have an advantage of making the point source by growing CNTs on a pointed structure. However, due to high local electric field there would be frequent arcing, which will ultimately damage the CNTs at the tip.

### 3.2 X-ray image of breast specimen

The portable and compact open type x-ray system with CNT emitters on a non-patterned substrate was operated at an anode voltage of 30 kV to take the x-ray images of removed breast specimen under the guidance of a professional radiologist. Normally, the required range is 25-50 kV, depending on the anode material and breast density type [16]. Figure 6(A) shows the optical image of a removed breast specimen during the surgery. Figure 6(B) and (C) are the respective x-ray images. From these images, the radiologists confirmed that the image with better brightness and contrast could be taken at a bias voltage of 30 kV with an anode current of 0.1 mA and exposure for 3 sec. The malignant breast tumor, as seen inside the red circles, was observed, without calcifications. Based on this result, the radiologist confirmed that smaller dense cancer cells could be detected by the CNT based X-ray system. Further research is needed to calculate the focal spot of the electron beam produced by the CNT field emitters. Experts also confirmed that the cancer lesions observed by this method seemed darker compared to those observed by conventional filament-based X-ray systems. This could be due to the generation of high intensity x-rays by the tungsten target.

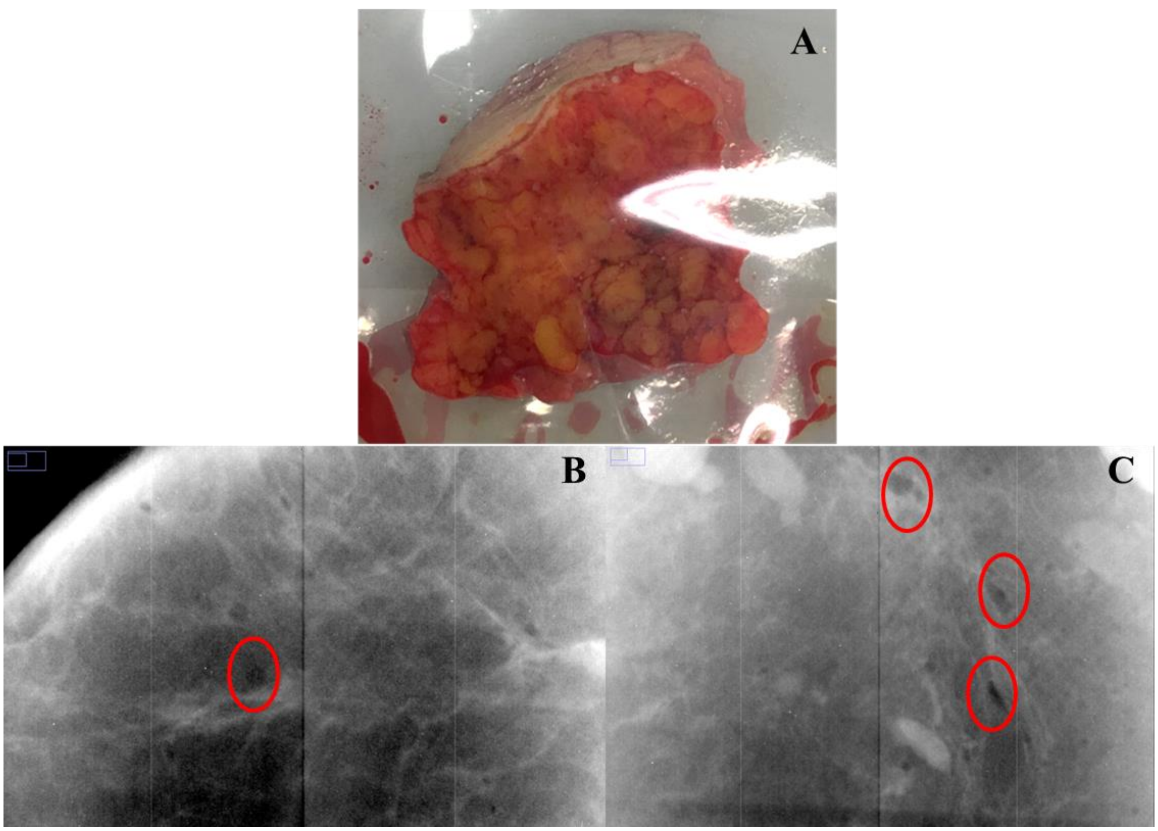


Figure 6: (A) the optical image and (B-C) x-ray images of surgically removed breast specimen tissue.

## 4. CONCLUSION

In this study, we demonstrated the working of a 2,5 inch compact open-type x-ray system with CNT field emitters. The system can be operated in the surgery room and can efficiently detect cancer cells on breast specimens compared to the conventional pathological examination. For high-resolution x-ray imaging, we developed a pointed electron source on a metal substrate. With further research on the pointed electron source and more preclinical trials, an efficient x-ray system can be developed that can replace the current filament based breast specimens. The X-ray system proposed herein has the advantage of being portable and can effectively reduce the surgery time for both surgeons and patients.

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