Journal of Medical Imaging

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Shinsuke Sasada
Norio Masumoto
Hang Song
Keiko Kajitani
Akiko Emi
Takayuki Kadoya
Koji Arihiro
Takamaro Kikkawa
Morihiro Okada

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Shinsuke Sasada,^{a,*} Norio Masumoto,^a Hang Song,^b Keiko Kajitani,^a Akiko Emi,^a Takayuki Kadoya,^a Koji Arihiro,^c Takamaro Kikkawa,^b and Morihito Okada^a

^aHiroshima University, Research Institute for Radiation Biology and Medicine, Department of Surgical Oncology, Minami-Ku, Hiroshima, Japan

^bHiroshima University, Research Institute for Nanodevice and Bio Systems, Higashi-hiroshima, Japan

^cHiroshima University Hospital, Department of Pathology, Minami-Ku, Hiroshima Japan

Abstract. Microwave breast imaging is a painless and nonradiation method. This pilot study aimed to evaluate the detective capability and feasibility of a prototype of a portable breast cancer detector using a radar-based imaging system. Five patients with histologically confirmed breast cancers with a minimum diameter of 1 cm were enrolled in this study. The antenna array dome of the device was placed on the breast of the patient in a supine position for 15 min per single examination. The primary endpoint was a detection rate of breast cancers. The secondary endpoints were positional accuracy and adverse event. All five targeted breast tumors were detected and were visualized at the sites confirmed by other diagnostic modalities. Among five tumors, one was not detected via mammography because of heterogeneously dense breast and another was a microinvasive carcinoma of invasive tumor size 0.5 mm. No study-related adverse events occurred. The prototype of a portable breast cancer detector has sufficient detective capability, is safe for clinical use, and might detect an early stage breast cancer, such as noninvasive carcinoma. Future developments should focus on further decreasing the size of the machine and shortening inspection time. © 2018 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.JMI.5.2.025502](https://doi.org/10.1117/1.JMI.5.2.025502)]

Keywords: breast cancer; microwave imaging; detectability; screening; ultrawideband radar; dome antenna.

Paper 18056R received Mar. 18, 2018; accepted for publication May 31, 2018; published online Jun. 13, 2018.

1 Introduction

Breast cancer is the most common malignancy among women worldwide and the second leading cause of cancer-related death.¹ Mammography is a standard screening examination and has been demonstrated to reduce breast cancer mortality in a meta-analysis of randomized controlled trials.² However, mammography has several limitations, such as low sensitivity for dense breast, pain, radiation exposure, and accessibility.^{3–6} Therefore, more convenient, accessible, and painless methods with no radiation exposure are required. Although ultrasonography meets these requirements, a high false-positive rate is a major problem in this imaging modality.^{7,8}

Recently, the electrical and dielectric properties of breast cancer have been reported to differ from those of normal tissue;^{9,10} as such, the microwave imaging technique has been developed for breast imaging. The microwave radar-based breast imaging techniques can detect breast cancer by measuring the time of flight of the reflected microwaves.^{11–17} The radiation-free microwave imaging method is expected to be an alternative to screening mammography. In a clinical evaluation of 86 symptomatic patients, a prototype of an ultrawideband radar scanner has detected breast masses with a sensitivity of 74%.¹⁸ In addition, the variability of the breast dielectric properties has been assessed by monitoring healthy patients over a long period.¹⁹ However, these conventional prototypes use vector network analyzers, resulting in heavy instruments and high costs.

Although some groups have developed compact microwave imaging systems,^{20–22} they are yet to be applied in the clinical setting. Therefore, we developed a prototype of a compact breast tumor detector using complementary metal-oxide-semiconductor (CMOS)-integrated circuits and a microwave radar-based imaging system.^{23–29} This pilot clinical study was conducted to evaluate the capability of our prototype to detect breast tumors in patients with breast cancer with a minimum diameter of 1 cm.

2 Patients and Methods

2.1 Patients

We recruited five patients with histologically confirmed breast cancers in this clinical study. The eligibility criteria were as follows: women aged over 20 years; tumor size ≥ 1 cm confirmed with at least two of the following imaging examinations: mammography, breast ultrasonography, contrast-enhanced magnetic resonance imaging (MRI), and ¹⁸F-fluorodeoxyglucose-positron emission tomography (PET), and written informed consent. The key exclusion criteria were history of chemotherapy or radiotherapy; hypersensitivity to acrylonitrile butadiene styrene plastic resin, which were used for contact on the skin surface and having a cardiac pacemaker.

The Institutional Review Board of the Hiroshima University Hospital approved this study. All procedures performed involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964

*Address all correspondence to: Shinsuke Sasada, E-mail: shsasada@hiroshima-u.ac.jp

Helsinki declaration and its later amendments or comparable ethical standards.

2.2 Study Examination Protocol

The structure and design of the detector were previously described.³⁰ The detector consists of CMOS integrated circuits, which enable the generation and transmission of Gaussian monocycle pulse (GMP) trains and the control of a 4×4 cross-shaped dome antenna array using a single-port eight throw switching matrices (SP8T-SW). The dome antenna array consists of 16 elements, and each antenna element is composed of a square slot set in a ground plane on one side of a Duroid RT 6010 substrate with a relative permittivity of 10.2. A forked microstrip feed is formed on the other side, which splits from a 50-ohm feed into two 100-ohm to excite the slot in the wide bandwidth. The size of the antenna is $11 \times 13.1 \times 0.635$ mm. The center frequency and the bandwidth of the antenna are 6 and 6.7 GHz, respectively. The dome shell is made of acrylonitrile butadiene styrene to hold the antennas. The detector measures $19.1 \times 17.7 \times 18.8$ cm and weighs 2 kg [Fig. 1(a)]. The detector system is controlled using a laptop computer [Fig. 1(b)]. The antenna array dome of the detector was placed on an ipsilateral breast of the patient without any coupling liquid in a supine position and held by hand or supported by hanging on a stand to keep it stationary [Fig. 1(c)]. The antenna array emits GMP signals with the pulse duration of 160 picoseconds at a repetition frequency of 100 MHz to illuminate the breast tumor, and receives the reflected signal in turn. It is then rotated at 3-deg step from 0 deg to 360 deg using a step motor. A single inspection yielded 120 sets of data acquired in 15 min. The received signals were converted from analog to digital via a 12-bit analog-to-digital converter (ADC). Each signal consists of 2048 measured samples, equivalent to 20 ns, and the signal is averaged for 2048 times to reduce the random error. The GMP signal with 160 mVpp (-12 dBm) is generated, and 6 dBm GMP is transmitted to the antenna through SP8T-SW. Part of the signal is lost in the human breast; as such, the signal arriving at the target is -27 dBm. The received signal at the receiver SP8T-SW is -51.5 dBm; thus, the signal is

amplified up to 3.5 dBm (42.3 mVpp) at the ADC. All data were saved and transferred to the laptop for offline processing.

2.3 Endpoints and Assessment

All patients underwent radical surgery on the day after the study examination, and pathological assessment was performed. The primary endpoint was the detection rate of malignant breast tumor, which was defined as the frequency of detectable tumors to the target breast ones. Secondary endpoints were accuracy of the position of the detected breast tumor and adverse events. Tumor position was assessed based on SEER Program Coding and Staging Manual 2015; Coding Guidelines Breast.³¹

3 Results

Between February and March 2017, five patients who were diagnosed with malignant breast tumors at Hiroshima University Hospital were enrolled in this study. The patient characteristics are shown in Table 1. All patients had invasive carcinomas and were estrogen and progesterone receptor positive. Among them, three were positive for human epidermal growth factor receptor 2 (HER2). All five breast tumors were detected by our prototype at a 100% detection rate. Regarding positional accuracy, all tumors were visualized at the same position as the site detected via other imaging modalities. Figure 2 shows the results of three representative cases: tumor position, images of study examination, mammography, ultrasonography, contrast-enhanced MRI, and breast PET.

Although almost all tumors were identified using all imaging modalities, a tumor of case 2 was invisible via mammography because of heterogeneously dense breast (Fig. 2; case 2-d). A tumor of case 3 was pathologically diagnosed using resected specimen as microinvasive carcinoma with invasive tumor size of 0.5 mm and tumor extent of 16 mm. The prototype clearly visualized both tumors. As shown in Fig. 3, the tumor site is consistent between the tumor image acquired using the prototype and the resected specimen in case 4.

No adverse events or equipment malfunction occurred during the study period. In addition, this study also never adversely affected patient treatment.

Fig. 1 Overview of the microwave breast tumor detector. (a) Appearance of the prototype device and (b) perspective of the examination room. The detector was connected to a laptop through a USB cable. (c) The antenna array dome of the detector was placed on the breast of a patient in a supine position and held by hand or supported by hanging on a stand to keep it stationary.

Table 1 Patient characteristics.

Case	Age (y)	Tumor side	Tumor location	Histology	Tumor size (cm)								
					Pathological invasive size	MMG	US	MRI	PET	ER	PgR	HER2	Ki-67 (%)
1	67	Left	Upper-inner	IC-NST	2.5	2.3	2.1	2.1	1.6	+	+	+	13
2	43	Right	Upper-outer	IC-NST	1.1	–	2.6	1.5	1.4	+	+	+	20
3	73	Left	Upper-inner	Microinvasive	0.05	3.4	3.6	2.6	3.3	+	+	–	17
4	58	Left	Central	IC-NST	2.8	2.6	2.1	2.8	2.5	+	+	+	20
5	36	Left	Upper-inner	IC-NST	2.5	1.9	1.9	2	1.4	+	+	–	47

Note: ER, estrogen receptor; HER2, human epidermal growth factor receptor 2; IC-NST, invasive carcinoma of no special type; MMG, mammography; MRI, magnetic resonance imaging; PET, positron emission tomography; PgR, progesterone receptor; SUV, standardized uptake value; US, ultrasonography.

Fig. 2 Tumor location and inspection images of three representative cases. (a) Tumor location, (b,c) images of study examination, (d) mammography, (e) ultrasonography, (f) contrast-enhanced magnetic resonance imaging, and (g) breast positron emission tomography. Arrows point to breast tumors.

4 Discussion

This clinical study demonstrated that the prototype of a portable impulse-radar-based breast cancer detector had a sufficient detection rate and positional accuracy for human breast cancers. The impulse-radar breast imaging device was developed as a painless and nonradiation screening method using a CMOS-integrated circuit module.^{24,26–29} The device reported previously is heavy and is stationary.¹⁸ We tried to downsize the equipment and shorten the inspection time.^{23,25} Other prototypes have been developed previously. Prototype-1 measured 45.0 × 30.0 × 12.1 cm in size, and a single measurement took 3 days.²⁵ Meanwhile, prototype-2 measured 28.5 × 22.5 × 9.5 cm, and a single measurement took 7 h.²³ In this study, we adopted a 4 × 4 cross-shaped dome antenna array covering the breast and a time-of-flight method and developed a handheld version (prototype-3 used in this study) measuring 19.1 × 18.8 × 17.7 cm, and

a single inspection using the prototype lasted only 15 min. It can be reduced to 3 min when the antenna array rotates at 15-deg step from 0 deg to 360 deg, yielding 24 sets of data without degradation of the images. Downsizing the device and shortening the examination time make it convenient and accessible for inspection. Factors limiting access to healthcare, such as living in rural areas, cause patients to forego mammographic breast screening.³² This portable detector can help improve the rate of breast cancer screening even in rural communities with geographical disadvantage. We assessed the performances of the prototype step by step. First, we evaluated the detective capability of the prototype using a breast tumor phantom that consisted of a block of bacon measuring 1 cm³ in size embedded in a silicone-based breast prosthesis.³⁰ The prototype successfully visualized the target at the accurate embedded position. Subsequently, the

Fig. 3 Comparison between images acquired by the prototype and the resected specimen. (a) Tumor position, (b) confocal imaging result, (c) 3-D display of the imaging area, (d) sagittal image of confocal imaging, and (e) sagittal section of surgical specimen. Dotted line and arrows show breast cancer.

accuracy of the device was assessed by comparing the breast imaging reconstructed by the detector with the resected breast specimens obtained through mastectomy. The breast cancers were successfully recognized at the positions with the pathological diagnosis.³⁰ Thereafter, the detective capability of the prototype was assessed for patients with breast cancers in this clinical study. The portable microwave-radar detector reliably visualized breast tumors with a size of 1 cm or more. In addition, the temperature transition of the instrument surface was measured, and it did not exceed the body temperature within 20 min of examination, indicating that the possibility of low-temperature burn injury from this device was extremely low. No patient complained of thermal sensation discomfort during the examination.

This study indicated that the impulse-radar detector had two significant advantages as follows. First, it detected a breast cancer that could not be recognized via mammography in a patient with heterogeneous dense breast (case 2). This result suggests that impulse-radar breast imaging can be used to screen for breast cancers in Asian young women who have dense breasts.^{5,33–37} Second, the device also detected a microinvasive carcinoma with an invasive tumor size of 0.5 mm (case 3) and has the potential to detect noninvasive carcinomas. Given that breast screening is important in early detection of breast cancer, our device may be helpful in increasing the rate of early detection of breast cancer.

The results of this preliminary study suggest that the prototype of the portable impulse-radar breast tumor detector has adequate detective capability and feasibility for clinical application and can detect early stage breast cancer. However, to improve convenience, the detector needs to be downsized further, and the examination time should also be shortened.

In addition, the detector should be able to distinguish benign tumors from breast cancers. Future studies should address these challenges.

Disclosures

The authors have declared no competing financial interests.

Acknowledgments

We thank Prof. Michihiro Hide for his helpful input. This work was supported by the Advanced Research and Development for Medical Innovation (16hm0102022h0004), Japan Agency for Medical Research and Development (AMED); Grant-in-Aid for Scientific Research (A) (25249050), Japan Society of the Promotion of Science (JSPS).

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Shinsuke Sasada is an assistant professor of breast surgery at Hiroshima University Hospital, Japan and received his PhD from Hiroshima University. His research interests are development of breast imaging using microwave and nuclear medicine.

Norio Masumoto is an assistant professor of breast surgery at Hiroshima University Hospital, Japan and received his PhD from Hiroshima University. His research interests are breast cancer imaging.

Hang Song received his BS and MS degrees in electronic science and technology from Tianjin University, China, in 2012 and 2015, respectively. Currently, he is pursuing his PhD with Hiroshima University, Japan. His research interests are microwave breast cancer detection system, complex permittivities of breast cancer tissues, and antenna design.

Keiko Kajitani is a breast oncologist at Hiroshima University Hospital, Japan and received her PhD from Hiroshima University. Her research interests are breast cancer imaging.

Akiko Emi is a breast oncologist at Hiroshima University Hospital, Japan and received her PhD from Hiroshima University. Her research interests are breast cancer imaging.

Takayuki Kadoya is an associate professor of surgical oncology at Research Institute for Radiation Biology and Medicine, Hiroshima University Hospital, Japan and received his PhD from Hiroshima University. His research interests are breast cancer imaging.

Koji Arihiro is a professor of pathology at Hiroshima University Hospital, Japan and received his PhD from Hiroshima University. His research interests are breast cancer pathology and gene instability.

Takamaro Kikkawa received his BS and MS degrees in electronic engineering from Shizuoka University, Japan and his PhD in electronic system from the Tokyo Institute of Technology. He is a professor at the Graduate School of Advanced Sciences of Matter and the director of the Research Institute for Nanodevice and Bio Systems. His research interests include wireless and wired interconnect technologies, impulse-radio-CMOS transceiver circuits with on-chip antennas, and impulse-radar-based CMOS breast cancer detection system.

Morihito Okada is a professor of surgical oncology at the Research Institute for Radiation Biology and Medicine, Hiroshima University Hospital, Japan and received his PhD from Kobe University. His research interests are thoracic oncology, PET imaging, and less-invasive surgery.