Experimental Evaluation of Thin Bone Fracture Detection Using Microwave Imaging

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***Abstract*—Microwave imaging is a promising candidate modality for the detection of fractures in superficial bones. We propose a simple dedicated experimental setup and use it to evaluate experimentally the feasibility of detection and location of thin transversal fractures in an animal bone. A single small Vivaldi antenna scans the bone along its length in two longitudinal planes, and collects the monostatic scattered fields in the 8.3-11.1 GHz frequency range. The image is reconstructed using a wave migration algorithm. Tests were carried on an ex-vivo animal leg bone with an induced transversal fracture. The results showed that transversal bone fractures can be detected down to 0.35 mm thickness. The system is attractive for a practical application because it is contactless, operated in air, non-ionizing, simple and comfortable for the patient. It can be used e.g. by first responders in the field, or in low-income settings.**

***Index Terms*—Microwave imaging, bone fracture detection, medical imaging, microwave system.**

I. Introduction

Microwave imaging (MWI) is an promising modality for screening animal or human parts of the body and has been studied for breast cancer detection, of brain hemorrhage to name a few examples. Here propose it to detect thin fractures in superficial bones. The technique is safe, non-invasive, non-ionizing, and potentially low-cost. It is attractive for instance for repeated monitoring or in low-income settings.

Our setup is based on a microwave monostatic radar system that illuminates the body with an electromagnetic field, and retrieves the scattered field from healthy and injured tissues. The signals are post-processed using an inversion algorithm to produce an image, which allows identification of fractures and its location. This process relies on the change, in the region of the fracture, of the electromagnetic field interaction with the bone.

Nowadays, several research teams around the world are evaluating the feasibility of medical diagnostics using MWI. In [1] and [2] the authors used a free space device to detect breast cancer. Studies in [3], [4] and [5] describe the use of the MWI technique to detect human brain hemorrhagic strokes. In [6], the reconstruction of bone profiles is investigated using a manufactured phantom prepared with animal tissues. The whole system is immersed in a coupling medium composed of a complex mixture. This approach is very unattractive for a practical application, and complicates the setup.

In [7] the authors used an adapted setup, based on a previous clinical prototype Mammowave [1], to detect longitudinal bone fractures and lesions in a simplistic phantom. The solution requires a fixed and bulky setup, which limits the portability and increases the cost for practical applications.

Another work presented in [8] proposed a compact system to detect bone fractures using a planar electromagnetic bandgap sensor with 11.4 mm x 80 mm dimension. That study uses a realistic phantom with 1- and 2-mm fractures. However, the system is very sensitive to the contact of the antenna with each scanned point of the skin, which difficult to maintain constant using the proposed rigid non conformal sensor.

Recently, we presented a preliminary study to detect and locate small transversal bone fractures with 0.25 mm thick, by simulation [9]. In the present paper, we present experimental results to detect and locate small transversal bone fracture, about 0.35 mm thickness. We present also a compact system operating that allows scanning in two planes with 30° angular separation, which is simple to fabricate and use in the field. The configuration is contactless and does not need immersion liquids. The device uses a single Vivaldi antenna in radar mode, operating in the 8.3-11.1 GHz frequency range. An *ex-vivo* animal bone with a small induced fracture of about 0.35 mm thickness, is used to evaluate the system. The image is reconstructed using a range migration algorithm [10].

II. Experimental Configuration

A. Microwave imaging system

Fig. 1 shows the proposed prototype system. A MDF (Medium Density Fiberboard) boxed structure was fabricated, with an aperture to introduce the arm or leg in a real application, for scanning. The antenna fixture translates longitudinally with the help of a linear guided system, using a precision lead screw connected to a NEMA 17 motor. the antenna scan position is controlled by an Arduino.

Measurements were performed in two planes (Position 1 and Position 2). At the current stage of development, the change between the two positions is manually made. In both measurements the distance between the bone and antenna was kept constant.

Measurements were performed in the frequency-domain between 8.3 GHz and 11.1 GHz using an Agilent E5071C Vector Network Analyzer (VNA) connected to the Vivaldi antenna. The acquisition $s_{11}(x_i, f_l)$ is done at $i = 1 \dots N_a$ uniformly distributed antenna positions along the longitudinal scan axis.

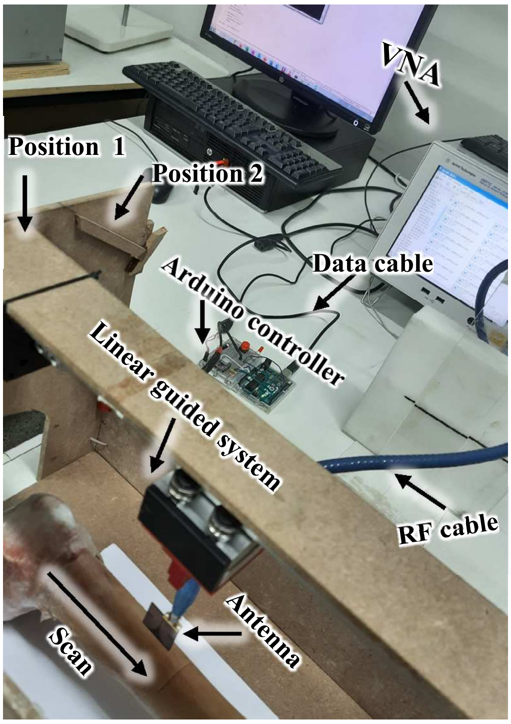

Fig. 1 Overview of proposed microwave imaging device.

In order to maintain the structure compactness, the wideband antenna had to be optimized to reduce its size, while keeping a stable and adequate near-field response across the band. It is a Vivaldi antenna operating in the 8.3-11.1 GHz frequency band. It is fabricated with ROGERS 5880 substrate, with $\varepsilon_r = 2.2$ and $\tan\delta = 0.0009$. The overall dimension are $L \times W = 28.01$ x 29.1 mm [9]. The reflection coefficient (s_{11}) measured in free space is less than −10 dB over the frequency range of interest Fig. 2.

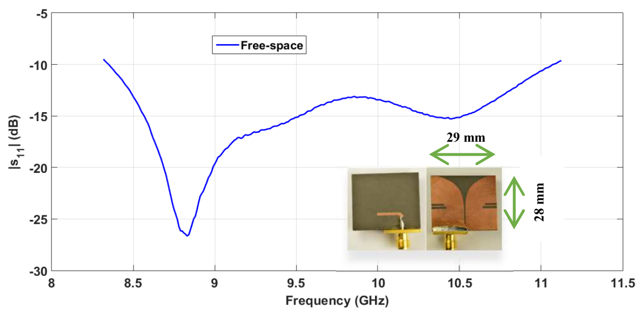

Fig. 2 Vivaldi antenna prototype and reflection coefficient of the antenna in free-space.

B. Ex-vivo sample

An animal tibia with 40-mm diameter and 150-mm length was used to mimic the human leg. A transversal cut was opened in the mid section of the bone about 0.35-mm thick and 20-mm deep, as shown in the Fig. 3.

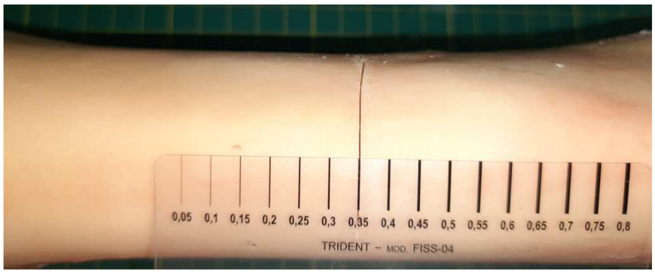

Fig. 3 Animal tibia used with an induced fracture.

The bone was kept refrigerated and hydrated until the measurement. The dielectric properties of the used animal tissues were measured in-house for most accurate characterization of the scenario.

C. Signal processing

The bone is aligned with the *x*-axis, and the fracture is aligned along z. The antenna performs a linear scan parallel to the *x*-axis, in the *xz*-plane. The position 1 is considered at 0°. Then, another scan was performed at a secondary plane, tilted 30° from the first scan plane, position 2, as shown in the Fig. 1. P_{Bone} designates the bone boundary at coordinates $(x_{Bone}, y_{Bone}, z_{Bone})$, while (x, y, z) defines the test point *P*.

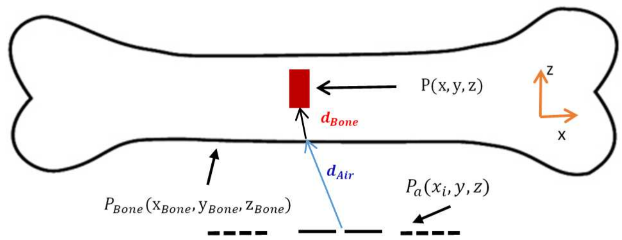

Fig. 4 Representation of the microwave imaging setup with an antenna operated in radar mode, linear scan on the x-axis and depth on the z-axis.

The antenna acquires $s_{11}(x_i, f_l)$ at $i = 1 \dots N_a$ uniformly distributed antenna positions $P_a(x_i,\ y,\ z)$, and at each of these positions, scans $l = 1 \dots N_f$ frequencies in the [8.3 – 11.1] GHz range. The image is reconstructed in the same plane that contains the antenna travel path (x-axis) and the z-axis, therefore the imaging algorithm is treated as a 2D problem.

The $s_{11}(x_i, f_l)$ signal is measured in two different planes, the first scan at the 0° (position 1), and the second scan at the 30º (position 2), the scans are made not simultaneously. The bone is kept fixed all the time of the measurements.

The Fermat principle is used to calculate the distances between the antenna and any pixel inside the bone assumed as an homogeneous dielectric [11]. The imaging algorithm is based on wave migration [9], [10].

III. EXPERIMENTAL RESULTS

The animal tibia was properly aligned with the scanning x-axis. The tip of the antenna was $z_{Bone} = 13$ mm away from the bone at its mid length. The scan comprised $N_a = 110$ points in the $0 \text{ mm} \le x_i \le 110$ mm interval, with $z = 0$, $y = 0$. The fracture is well identified and located at the actual position for both measured planes, as shown in Fig. 5, and Fig. 6.

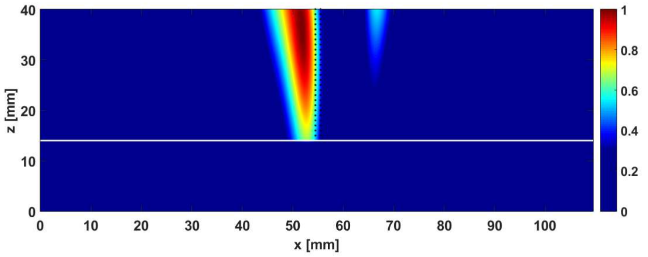

Fig. 5 Reconstructed image of ex-vivo animal bone obtained from measurements, in a planar section. The antenna scans at $0 \text{ mm} \le x_i \le 110$ mm, $z = 0$ and at position 1. The fracture is about 0.35 mm. The white contour identifies the bone limit..

To observe the fracture in another plane, the linear guided system is tilted 30° from the first scan plane, and the scan is repeated.

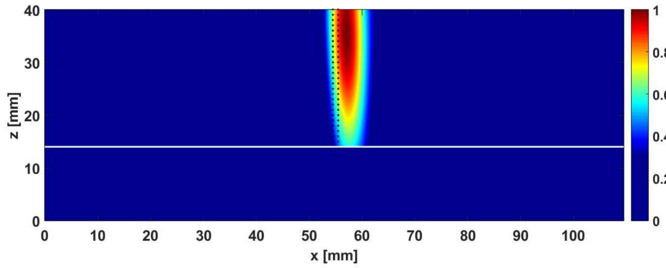

Fig. 6 Reconstructed image of *ex-vivo* animal bone obtained from measurements, in a planar section. The antenna scans at $0 \text{ mm} \le x_i \le 110$ mm, $z = 0$ and at position 2. The fracture is about 0.35 mm. The white contour identifies the bone limit.

Tests have been made with different animal bones, with equally good results. They show that the system is robust in detecting and locating small fractures close to real scenario. The approach of scanning in multiple longitudinal planes may be used to detecting other types of fractures, such as oblique ones.

IV. CONCLUSION

In this paper we experimentally evaluate the strategy for MWI detection of small thick transversal bone fractures. The system is tested in a setup very similar to what could be used clinical environments. For this test, a thick animal bone was used with a thin 0.35 mm thickness induced fracture.

Our system does not require any coupling medium to perform the detection, being a more realistic setup for future clinical applications. It is contactless, noninvasive, compact, and potentially portable and low cost.

Initial results using a transversal fracture scanned in two different planes show the feasibility to detect and locate other types of fractures. We will investigate the detection and location using oblique fractured bones in future work.

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REFERENCES

[1] A. Vispa, L. Sani, M. Paoli, A. Bigotti, G. Raspa, N. Ghavami, S. Caschera, M. Ghavami, M. Duranti e G. Tiberi, "UWB device for breast microwave imaging: phantom and clinical validations," Measurement, vol. 146, pp. 582-589, November 2019.

[2] J. M. Felício, J. M. Bioucas-Dias, J. R. Costa e a. C. A. Fernandes, "Microwave Breast Imaging Using a Dry Setup," EEE Transactions on Computational Imaging, vol. 20, pp. 167-180, July 2020.

[3] A. T. Mobashsher, A. Mahmoud e A. M. Abbosh, "Portable Wideband Microwave Imaging System for Intracranial Hemorrhage Detection Using Improved Back-projection Algorithm with Model of Effective Head Permittivity," Scientific Reports, vol. 6, February 2016.

[4] A. E. Stancombe, K. S. Bialkowski e a. A. M. Abbosh, "Portable Microwave Head Imaging System Using Software-Defined Radio and Switching Network," IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology, vol. 3, nº 4, pp. 284-291, December 2019.

[5] J. A. T. Vasquez, R. Scapaticci, G. Turvani, G. Bellizzi, D. O. Rodriguez-Duarte, N. Joachimowicz, B. Duchêne, E. Tedeschi, M. R. Casu, L. Crocco e a. F. Vipiana, "A Prototype Microwave System for 3D Brain Stroke Imaging," Sensors, vol. 20, nº 9, p. 2607, May 2020.

[6] G. Ruvio, A. Cuccaro, R. Solimene, A. Brancaccio, B. A. Basile e M. J., "Microwave bone imaging: a preliminary scanning system for proof-of-concept," Healthcare Technology Letters, vol. 3, pp. 218-221, June 2016.

[7] B. Khalesi, B. Sohani, N. Ghavami, M. Ghavami, S. Dudley e a. G. Tiberi, "Free space operating microwave imaging device for bone lesion detection: a phantom investigation," IEEE Antennas and Wireless Propagation Letters, p. 5 pages, October 2020.

[8] V. S. Ramalingam, M. Kanagasabai e a. E. F. Sundarsingh, "A Compact Microwave Device for Fracture Diagnosis of the Human Tibia," IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 9, nº 4, pp. 661-668, April 2019.

[9] K. C. Santos, C. A. Fernandes e a. J. R. Costa, "A study on the sensitivity of microwave imaging for detecting small-width bone fractures," em 15th European Conference on Antennas and Propagation (EUCAP), Germany, April 2021.

[10] J. M. L.-S. a. J. Fortuny-Guasch, "3-D radar imaging using range migration techniques," IEEE Transactions on Antennas and Propagation, vol. 48, pp. 728 - 737, May 2000.

[11] A. T. Mobashsher, A. M. Abbosh e a. Y. Wang, "Microwave System to Detect Traumatic Brain Injuries Using Compact Unidirectional Antenna and Wideband Transceiver With Verification on Realistic Head Phantom," IEEE Transactions on Microwave Theory and Techiniques, vol. 62, nº 9, pp. 1826-1836, September 2014.