Microwave non-contact imaging of subcutaneous human body tissues

Andrey Kletsov¹ ✉, Alexander Chernokalov¹, Alexander Khripkov¹, Jaegeol Cho², Sergey Druchinin³

¹Samsung R&D Institute Russia, Samsung Electronics, Moscow 127018, Russian Federation

²DMC R&D Center, Samsung Electronics, Suwon 443-742, Republic of Korea

³Geological Prospecting LLC, Moscow 127254, Russian Federation

✉ E-mail: a.kletsov@samsung.com

Published in Healthcare Technology Letters; Received on 2nd February 2015; Revised on 10th June 2015; Accepted on 17th June 2015

A small-size microwave sensor is developed for non-contact imaging of a human body structure in 2D, enabling fitness and health monitoring using mobile devices. A method for human body tissue structure imaging is developed and experimentally validated. Subcutaneous fat tissue reconstruction depth of up to 70 mm and maximum fat thickness measurement error below 2 mm are demonstrated by measurements with a human body phantom and human subjects. Electrically small antennas are developed for integration of the microwave sensor into a mobile device. Usability of the developed microwave sensor for fitness applications, healthcare, and body weight management is demonstrated.

1. Introduction: Mobile healthcare practices (health data collection, delivery of healthcare information and fitness personal coaching) are of the utmost importance for the improvement of life quality [1]. Seamless healthcare monitoring will become a part of everyday life as soon as health sensors become widely available. Still, integration of health sensing functions into mobile or wearable devices is at an early stage now.

Home-applied personal human body imaging would impact efficiency control for body weight management and fitness training. At present, monitoring of body mass index and average composition are available using bio-impedance spectroscopy metres. However, fitness training of particular body parts benefit from precise measurement of a subcutaneous fat for a target body part, rather than the average amount of fat in the entire body. Skinfold caliper is not comfortable for home usage; magnetic resonance imaging and ultrasonic devices are only applicable for clinical practices.

In recent decades, a microwave human body imaging technique was applied for various medical applications, including non-invasive human body imaging [2], diagnostics of a breast cancer [3] and non-contact monitoring of vital signs [4].

This Letter is devoted to the microwave human body imaging technique applied for depicting the subcutaneous fat structure changes in particular parts of the body during a course of exercises or dieting. The fat tissue structure is measured by analysis of microwave signal reflections from fat, skin and muscle tissue borders.

Accuracy of the subcutaneous fat tissue structure imaging is estimated using simulation models and experimentally validated for the human body phantom and adult human subjects. Synthetic aperture radar imaging is implemented by manual movement of the microwave sensor along the human body surface. Fat thickness measurement accuracy better than 2 mm was achieved, which is close to the resolution of the human body tissue imaging by an array of microwave sensors [3] surrounding the human body.

2. Structure of the microwave sensor: The microwave sensor comprises transmit and receive antennas which are to be placed above the human body surface (Fig. 1). Non-contact, through-clothing measurements are performed; specifically, direct galvanic contact to the skin is not required, any kind of light clothlike t-shirt and sensor's plastic cover could be placed between the skin and antennas during measurement. Distortions caused by the t-shirt could be removed as constant signal distortions.

Stepped-frequency continuous-wave approach [3] is implemented for improvement of the microwave sensor resolution. Measurements are performed in a frequency domain; a signal generator Hittite HMC732LC4B transmits a sequence of sinusoidal tones with 200 frequency steps within a 6–10 GHz band, controlled by a PLL Fujitsu MB15E03. Frequency band was selected as it is commonly used in ultra-wide band standards IEEE 802.15.4a, 802.15.6. Transmitter power level -41.3 dBm/MHz is chosen according to these regulations. Transmitted signals undergo reflections within the human body tissues, which are sensed by the receiving antenna. Signals from the receiving antenna are detected by a heterodyne receiver based on an RF/IF gain and phase detector AD8302. The receiver is intended for detecting amplitude attenuation and phase delay of the received signals compared with the transmitted signals.

Performance of the microwave sensor was tested using a vector network analyser, Agilent PNA-X N5247A, connected to transmit and receive antennas.

A series of measurements are performed during movement of the sensor along the body surface. At each on-body measurement position of the microwave sensor, amplitude attenuation and phase delay of the received signals are recovered for each sinusoidal tone. Time-domain waveforms with 50 ps time step are obtained by performing the inverse Fourier transform on the collected results at $F_{\max} = 10$ GHz. Interpolation of multiple pulse responses in time domain provides 10 ps time resolution, thus achieving required 2 mm spatial resolution.

Reflections from borders between different tissues are analysed for the subcutaneous fat tissue structure imaging. Reflection coefficients for fat–muscle border Γ_{F-M} and skin–fat border Γ_{S-F} are approximately defined as [5]

$$|\Gamma_{F-M}| \approx \frac{\sqrt{\epsilon_M} - \sqrt{\epsilon_F}}{\sqrt{\epsilon_M} + \sqrt{\epsilon_F}} \simeq 0.33,$$

$$|\Gamma_{S-F}| \approx \frac{\sqrt{\epsilon_S} - \sqrt{\epsilon_F}}{\sqrt{\epsilon_S} + \sqrt{\epsilon_F}} \simeq 0.38$$

Here, $\epsilon_F = 4.6$ is the fat permittivity, $\epsilon_M = 42.7$ is the muscle permittivity, and $\epsilon_S \approx 31.3$ is the skin permittivity (at 8 GHz) [6]. Thus, the most part of microwave energy is reflected at these borders. Large differences in dielectric permittivity is providing better

Figure 1 Structure of the microwave sensor

contrast compared with ultrasound systems, which are defined by density of tissues.

Antennas have bow-tie structures [7]. Antenna prototypes are fabricated with FR-4 dielectric, and $\varepsilon = 4.4$ tg $\delta = 0.02$ to better match antennas with fat tissue ($\varepsilon_F \approx 4.6$). Each antenna is $12 \times 12 \times 2.5$ mm in size, which allows its integration into the mobile device as shown in Fig. 2. A metal grounded shield is placed at the antenna back side to isolate imaging area from surrounding objects.

3. Measurement procedure and data processing for reconstruction of human body tissues: The microwave sensor shall be manually moved along the skin surface. A series of measurements are taken during this movement. Coordinates of each measurement position are located by an additional optical or mechanical motion sensor and utilised for equidistant measurements along the body's surface. At that, structure of the human body tissues is calculated using measurement results taken at a number of positions with relative coordinates of these positions. Thickness of the subcutaneous fat tissue is derived as a distance between the skin and the muscle layers.

The gap between antennas and skin causes parasitic signal reflections due to a high difference in the dielectric properties of the skin ($\varepsilon_s \approx 31$) and the air. At that, received signals from subcutaneous fat and muscle layers interfere with parasitic signals of direct coupling between the transmitting and receiving antennas through the air and the skin [2–4].

The signal path 'Tx antenna – skin – Rx antenna' is shorter than the signal path through human body tissues. Therefore a calibration signal could be defined as a minimum-phase signal [8]. At that, removal of reflections from skin tissue and reconstruction of subcutaneous fat tissue structure is done using inverse filtration methods [9, 10]. The calibration signal is generated by averaging time responses from all antenna positions on the skin. That calibration signal is subtracted from the raw data. As a result, pulses reflected from deep tissue borders are obtained.

4. Estimation of achievable microwave imaging accuracy:

Depth (or vertical) accuracy is defined as a distance between objects which can be resolved; it is proportional to the

Figure 2 Antenna size is $12 \text{ mm} \times 12 \text{ mm} \times 2.5 \text{ mm}$, which allows its integration into the mobile device

a Photograph of the antenna prototype with external cable connectors
b Antennas installed into the mobile device

Figure 3 Accuracy estimation by variation of the fat thickness in simulation model

wavelength λ_1 in body tissue. Objects can be confidently resolved in depth if the distance between them is $A_d \approx \lambda_1/3 \dots \lambda_1/2$, where λ_1 is the wavelength in tissues, $\lambda_1 \approx \lambda/\text{re}(\sqrt{\varepsilon'})$, λ is the wavelength in free-space. Objects which have sizes sufficiently smaller than the radar resolving possibility A_d are in Rayleigh region and have very weak reflection signal. For example, at 8 GHz frequency ($\lambda = 37.5$ mm) the wavelength in muscle tissues is $\lambda_1 = 5.9$ mm. At that, theoretical limit for depth accuracy is $A_d = 1.9$ mm.

Accuracy estimation was carried out using full-wave electromagnetic simulation as illustrated in Fig. 3. Signal propagation parameters are derived from the model with fat and muscle material properties [6].

Reflected pulse responses in time domain are depicted in Fig. 4 for fat thickness $d = 20$ mm stepped by $\Delta d = 2$ mm, normalised pulse magnitude is shown on the vertical axis.

The time shift of reflected signal pulses is caused by path length difference $L_2 - L_1$. Depth accuracy 2 mm for fat thickness measurement requires a 10 ps time resolution, achieved by the developed microwave sensor.

Maximum body tissues' reconstruction depth is limited by thermal noise. For the prototype with 80 dB dynamic range, maximum fat imaging depth is estimated as 70 mm.

5. Experimental test results for the human body phantom:

Performance of the proposed subcutaneous fat tissue imaging method is evaluated by experimental measurements on human body phantoms and for human subjects. An experimental setup was assembled for automatic measurements of amplitude and phase characteristics signal propagation through tissues between the transmitting and receiving antennas (Fig. 1).

Experimental calibration and measurement repeatability tests were carried out using the first human body phantom with stepped fat tissue layers made of FR-4 material, as FR-4 permittivity is close to that of fat. Dimensions of the first phantom layers are shown in Fig. 5b. Test results of ten independent measurements

Figure 4 Simulation results for time-domain pulse responses: fat thickness $d = 20$ mm, $\Delta d = 2$ mm

Figure 5 Fat tissue stepped phantom

a Second

b First

c Second

with the first phantom are provided in Fig. 6a and Table 1; root-mean-square error (RMSE) of fat thickness is below 1.21 mm and the maximum deviation is 1.72 mm.

Measurement accuracy better than 2 mm was confirmed using a second body phantom and fabricated using an agar-based mixture with polyethylene powder and hydrophilic additive [11, 12] (Figs. 5a and c). Experimental results for the second stepped body phantom are shown in Fig. 6b. Real step depth and measured error are provided for each depth of the second body phantom.

6. Experimental test results for human subjects: Fat thickness of human subjects was measured at the abdomen area through t-shirts, using an experimental measurement setup.

Measurements were conducted by the authors on themselves for several on-body positions. Measurement results were compared with reference data obtained using a fat caliper. Accuracy of the final product must be validated at the next step with detailed clinical trials.

Table 1 Test results for the human body phantom

Measurement results	Step 1	Step 2	Step 3	Step 4	Step 5
Max depth, mm	3.44	8.06	12.8	17.4	22.3
Min depth, mm	5.15	9.78	13.7	18.1	23
Mean depth, mm	4.29	8.92	13.2	17.8	22.7
RMSE, mm	1.21	1.21	0.615	0.495	0.474
Real depth	4.5	9	13.5	18	22.5

Table 2 Test results for human subjects

Subject number	Test 1	Test 2	Test 3	Mean	Reference caliper
1	18.4	17.2	18.1	17.9	17.8
2	16.9	16.7	16.3	16.6	17.3
3	11.8	11.6	11.7	11.7	10
4	20.3	19.8	20	20	20.4
5	10.4	12.2	9.3	10.6	11.7
6	12.1	14.1	14.1	13.4	12
7	12	12.3	10.1	11.5	9.5
8	9.4	4.1	4.7	6.07	5.9
9	12.8	14.6	12.6	13.3	13.2
10	20.8	21	19.9	20.6	18.8

All data is in millimetres

Accuracy of the caliper measurements was evaluated statistically, by ten consequential measurements of abdominal fat thickness repeated for ten subjects. According to the experimental results, RMSE for caliper measurements of subcutaneous fat thickness is below 1.28 mm.

A series of measurements were made during vertical movement of antennas along the abdomen area. Comparison of experimental results and reference caliper results are given in Table 2. Statistical measurements were made for ten subjects using the experimental setup. Results for fat thickness measurement carried out by the microwave sensor are in good agreement with the reference measurements obtained with the skinfold caliper.

Measurement results for tissues structure in 2D are depicted in Fig. 7. Data processing results depict detailed structure of the subcutaneous tissues in cross-section view (Fig. 7b). Each column of pixels is a time-domain response of the reflected signal (Fig. 7a) measured as the user moves the sensor along the skin surface. A repeatability test was conducted by a series of measurements on the same on-body path and on several abdomen parts (Fig. 8). The

Figure 6 Test results of ten independent measurements with the first and second phantoms. 'Deep, millimetres' is depth of measured reflections and 'distance, centimetres' is distance of the sensor's movement along the phantoms

a Experimental results for the first stepped body phantom

b Results for second phantom.

Figure 7 Signals processed from initial raw datasets. White spots correspond to peaks of reflected signals in time domain. Restored fat-muscle tissue border is marked with thin grey curve. Vertical axis is depth in millimetres

a Pulse response of depth reflections in a single measurement

b Image with reconstructed fat-muscle border

Figure 8 Photograph of the experimental measurement setup

Figure 9 Repeatability of the fat tissues depth measurement, five datasets are plotted for the same human subject

test results are shown in Fig. 9. Maximum variation for all measurements does not exceed 2 mm; RMSE of measurement results are below 0.8 mm.

It should be noted that good accuracy is achievable if the antennas are placed tightly to the surface of the skin or the clothes. This keeps constant conditions for the antenna–body interface, enabling extraction of the parasitic direct propagation signals as described in Section 3. Inhomogeneous air gaps or folds of clothing under the antennas results in poor removal of parasitic direct propagation signals.

7. Further applications: A developed method could be applied for monitoring of a visceral fat distribution in the abdomen area. Evaluation of fat percentage should be based on average body permittivity, measured by placement of antennas at different sides of the body and measurement of in-body signal time of flight. At that, the amount of the visceral fat is to be evaluated by subtracting the volume of the subcutaneous fat from the total volume of the body fat.

Further applications of health sensing in mobile devices may include a head imaging system for tumor detection, cardiopulmonary sensing (heart strength, vascular age and arterial stiffness) and analysis of inner body organs: for example, the liver and a kidney.

8. Conclusion: A new application for microwave human body imaging is demonstrated for management of body weight and fitness training. Feasibility is proven for 2D image reconstruction of the subcutaneous body tissues. Measurement accuracy is estimated in simulation models and demonstrated experimentally: RMSE of fat thickness measurement is below 1.21 mm, maximum deviation 1.72 mm, and maximum imaging depth 70 mm.

We have proven experimentally that taking a series of measurements while manually moving the microwave sensor along the skin surface achieves such accuracy, as if the microwave sensor had transmit and receive array antennas of large enough size to simultaneously cover all positions along the path. Developed measurement method enables the same imaging resolution of subcutaneous fat tissue structure as achieved by array of microwave sensors [3, 13].

The proposed microwave sensor is highly applicable for mobile and wearable devices. Compact size transmit and receive antennas are developed for the 6–10 GHz frequency band; synthetic aperture radar imaging method is disclosed. It enables home-applied personal healthcare and fitness applications: precise tracking of the body composition during the fitness course by measurement of the subcutaneous fat at various parts of the human body.

9. Acknowledgment: This paper is dedicated in memory of Prof. Sergey Druchinin.

10. Declaration of interest: Dr. Kletsov, Dr. Chernokalov, Dr. Khripkov and Dr. Cho have the patent pending “An ultra-wideband device for determining a profile of living body tissue layers and the corresponding method”.

11 References

- [1] ‘mHealth: new horizons for health through mobile technologies: based on the findings of the second global survey on eHealth’, Global Observatory for eHealth Series, 3 (World Health Organization, Geneva, Switzerland, 2011), ISBN: 978-92-4-156425-0
- [2] Elmissaoui T., Soudani N., Bouallegue R.: ‘Optimization of the UWB radar system in medical imaging’, *J. Signal Inf. Process.*, 2011, **2**, pp. 227–231, doi: 10.4236/jsip.2011.23031
- [3] Bassi M., Caruso M., Khan M.S., Bevilacqua A., Capobianco A., Neviani A.: ‘An integrated microwave imaging radar with planar antennas for breast cancer detection’, *IEEE Trans. Microw. Theory Tech.*, 2013, **61**, (5), pp. 2108–2118, doi: 10.1109/TMTT.2013.2247052
- [4] Gu C., Li C.: ‘From tumor targeting to speech monitoring: accurate respiratory monitoring using medical continuous-wave radar sensors’, *IEEE Microw. Mag.*, **15**, (4), 2014, pp. 66–76, doi: 10.1109/MMM.2014.2308763
- [5] Nicolson A.M., Ross G.F.: ‘Measurement of the intrinsic properties of materials by time-domain techniques’, *IEEE Trans. Instrum. Meas.*, 1970, **IM-19**, pp. 377–382, doi: 10.1109/TIM.1970.4313932
- [6] Gabriel C.: ‘Compilation of the dielectric properties of body tissues at RF and microwave frequencies’ (Department of Physics, King’s College, London, UK, 1996)
- [7] Balanis C.A.: ‘Modern antenna handbook’ (John Wiley & Sons, Hoboken, NJ, USA, 2008)
- [8] Claerbout J.F.: ‘Fundamentals of geophysical data processing’ (Blackwell Scientific Publications, Hoboken, NJ, USA, 1985)
- [9] Bond E.J., Li X., Hagness S.C., Van Veen B.D.: ‘Microwave imaging via space-time beamforming for early detection of breast cancer’, *IEEE Trans. Antennas Propag.*, 2003, **51**, (8), pp. 1690–1705, doi: 10.1109/TAP.2003.815446
- [10] Izyumov S.V., Druchinin S.V., Voznesenskiy A.S.: ‘Theory and methods of georadiolocation’ (Gornaya kniga, MGPU, 2008, Moscow, Russia, 2008), ISBN: 978-5-98672-098-2
- [11] Onishi T., Uebayashi S.: ‘Biological tissue-equivalent phantoms usable in broadband frequency range’, *NTT DoCoMo Tech. J.*, v.7 # 4
- [12] ‘TX products info data’. Available at <http://www.oilcenter.com/ProductInformationSheets/N-Z/Txproducts.pdf>
- [13] Mojabi P., Ostadrahimi M., Shafai L., LoVetri J.: ‘Microwave tomography techniques and algorithms: a review’. 2012 15th Int. Symp. on Antenna Technology and Applied Electromagnetics (ANTEM), Toulouse, France, 25–28 June 2012, pp. 1–4