Ultra-wideband (UWB) as imaging tool for diagnostic purposes

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Authors: C. Geyer¹, M. Helbig², U. Schwarz², J. Sachs², M. A. Hein², W. A. Kaiser¹, I. Hilger¹, ¹Jena/DE, ²Ilmenau/DE
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Purpose

The application spectrum of ultra-wideband (UWB) is currently growing [1]. For example, a number of studies demonstrate the use in the field of information and communication technologies (e.g. [2]), basically because of its ability to transfer large data sets over short distances.

Another application of UWB sensor systems comprises the localisation of objects by means of analysis of backscattered signals. The basic principle of this application is based on wave reflection which depends on the conductive and dielectric properties of the corresponding target. By evaluation of the ratio between emitted and received signals, a spatial localization can be achieved. This approach is assessed among others, for the identification of landmines or detection of objects and living organisms [3,4].

The use of UWB systems for biomedical applications has been investigated mostly on the basis of simulations. Different groups have already shown the fundamental practicability of UWB as an imaging tool in biomedical applications [5-7]. Thereby, the water content plays a key role, because it determines the tissue inherent dielectric properties ($\varepsilon' + j\varepsilon''$) [8]. Owing to the fact that the water content varies among the different human tissues, the application of UWB sensor systems in biomedical diagnostics offers a potentially broad bandwidth, and the advantages to potentially be a non-invasive, non-ionizing, expectedly cheap, easy and fast to accomplish imaging method.

The reflection of electromagnetic wave (here the UWB pulses) at dielectric boundary surfaces and interfaces represents the physical base of the approach. The dielectric properties of a material are characterized by its complex dielectric value $\varepsilon = \varepsilon' - j\varepsilon''$. The real part $\varepsilon'$ quantifies the ability of the material to focus electrical fields; it is tightly related to the index of refraction, $n = \sqrt{\varepsilon'}$. The dielectric absorptive losses occurring in the material is measured by the imaginary part $\varepsilon''$. Depending on the different dielectric values $\varepsilon_0$ and $\varepsilon_1$ of adjacent materials, a reflected signal will occur which is determined by the reflection coefficient:
The aim of this study was to assess the basic feasibility of ultra-wideband sensors for the discrimination of biological tissues with different water content, simulated by phantoms with defined dielectric properties. In principle, the interaction of ultra-wideband signals with the material under test can be detected using coaxial probes and/or antennas (dielectric spectroscopy). Dielectric spectroscopy with coaxial probes allows the determination of absolute dielectric values, but is restricted to a small measuring volume, which is determined by the cross-section of a conveniently calibrated coaxial probe. It will therefore be used as reference method to determine the permittivity of our phantoms, from which the absolute water content of different tissues can be derived by means of tissue-mimicking models [9,10].

Images were obtained by using antennas which illuminate the regions of interest from a distance. In contrast to coaxial probes, antennas radiate the energy within a wide beam and the received signal contains reflection components from different tissue areas with various dielectric values. Although this set-up complicates the signal interpretation as well as an efficient calibration, we show that images can be obtained anyhow by measurements using different antenna positions and adequate imaging signal processing (e.g. migration based algorithms), allowing the recognition of differences of the reflection intensity caused by the different dielectric values of various areas of the material under investigation.

**Methods and Materials**
Production of tissue mimicking phantom materials

Nine tissue-mimicking oil-in-gelatine phantoms were produced according to a protocol from Lazebnik et al. [11]. Briefly, gelatine (from 8.5 g to 17 g depending on the respective phantom; 180 bloom; Roth, Karlsruhe, Germany) was solved in a mix of p-toluic acid (from 0.05 g to 0.1 g; Sigma-Aldrich, Steinheim, Germany), n-propanol (2.5 ml to 5 ml; Roth, Karlsruhe, Germany) and distilled water (from 47.5 ml to 95 ml) by heating the solution in a water bath at temperatures of 95°C. Afterwards, the solution was cooled down to 50°C while rape oil (from 0 ml to 200 ml; Oelmühle GmbH + Co, Hamm, Germany) was tempered at 50°C. Gelatine- and oil-solution were mixed together by adding a surfactant (0.56 ml per ml of oil; Perovit; Henkel, Düsseldorf, Germany) and stirred vigorously. When having a temperature of 40°C, 37% formaldehyde (0.0108 g per ml of the gelatine solution; Roth, Karlsruhe, Germany) was added to the mixture, subsequently the emulsion was cooled down to 34°C and poured into a cylindrical mould (height = 3 cm; diameter = 6 cm). The oil concentration varied between 0 and 80% (v/v) to obtain a set of materials with different permittivity values.

Measurements of phantom dielectric properties

A network analyzer (HP 8753D Option 011 network analyzer) with a frequency bandwidth of 1 to 4 GHz and a coaxial probe was used to determine the dielectric properties of the phantoms. Before measurements, a three-term calibration using three standards (air, short circuit and 0.01 M NaCl; Sigma-Aldrich, Steinheim, Germany) was carried out. For phantom dielectric property determinations, the coaxial probe was selectively placed on the corresponding phantom materials at three different points at their surface. During measurements, an electrical signal was send out of the probe into the material object under test. The signal-reflections emerging from the object were measured by the same probe. The acquired data sets were analyzed and converted into dielectric values by the use of MATLAB (Version 7.3.0.267; The MathWorks, Inc., Natick, MA, USA).

x-y-z Scan with a M-sequence radar device

For two-dimensional imaging, the oil-in-gelatine samples were arranged in a prototype xyz-UWB-scanner (Fig. 1). The scanner consisted of a box (internal dimensions (length x width x height): 80 x 80 x 75cm) which was closed at five sides, which were insulated from spurious microwave radiation with aluminium-foils and microwave absorbers. The open side was oriented to the top. Tooothed belt drive facilities (isleautomation GmbH & Co. KG, Eichenzell, Germany) were mounted on the upper margins, and they served to move a retainer, on which two pyramidal horn antennas (10 cm x 8 cm x 23 cm) were fixed. By this way, the antennas could be moved in three dimensions: the horizontal plain (xy-plain) and the vertical (z-plain) one. By doing so, the maximal spatial field to be scanned was about 60 cm x 60 cm x 30 cm. The retainer movements were triggered by specific reprogrammed software using a controller (isleautomation GmbH & Co. KG, Eichenzell, Germany). The antennas were hold in a distance of 17 cm in z-plain orientation over
the phantoms. Imaging was carried out by means of scanning the xy-plane using a M-sequence (special order of pseudo-noise-sequences generated by a shift register [12]) sensor system from MEODAT® (Ilmenau, Germany) with a frequency bandwidth to 4.5 GHz. This sensor system, attached on a sledge (Fig. 1), was also transported by toothed belt drive facilities.

The digital signal processing was accomplished on the basis of an algorithm specifically adapted to this task. It yielded a two-dimensional image of the phantoms and their geometrical arrangement, which was compared with the true arrangement in the xyz-scanner.

**Images for this section:**

![Experimental setup of the three-axis UWB-scanner](image)

**Fig. 1:** Experimental setup of the three-axis UWB-scanner. Objects were placed in a box shielded against spurious microwave radiation with aluminium foil and microwave absorbers. Two pyramidal horn antennas were fixed on toothed belt drive facilities which were responsible for the motion of the retainer. The movements were triggered by specific reprogrammed software using a controller. The retainer with the antennas could be moved in the horizontal xy-plane and along the vertical z-direction. The two antennas
were connected by HF-cables with the M-sequence-UWB system, which was fixed on a sledge and also transported by the toothed belt drive facilities.
Results

Dielectric spectroscopy of the phantoms

While varying the oil-concentration, the identification of distinct permittivity values \(\varepsilon'\) (Fig. 2A) and \(\varepsilon''\) (Fig. 2B) of the different oil-in-gelatine phantoms was possible. Both the real and the imaginary values of the permittivity decreased with increasing oil concentration for all samples. While the phantom produced without oil (0% oil in Fig. 2A and 2B) showed values between 58 and 64 for the real part and between 13 and 16 for the imaginary part of the permittivity in the frequency range between 1 and 4 GHz, the phantom containing 40% oil showed comparatively lower permittivity values \(\varepsilon'\) between 29 and 33 and \(\varepsilon''\) between 5 and 6. The lowest permittivity was given by the 80% oil-in-gelatine phantom, namely \(\varepsilon'\) between 8 and 10 and \(\varepsilon''\) between 0.5 and 1. As a comparison, the results for pure distilled water and pure oil were also given in Fig. 2A and Fig. 2B.

Imaging results of the arrangement of nine phantoms

Since the phantom arrangement could be well reproduced, while every single phantom could be depicted as two-dimensional circular structures colour-coded image in Fig. 3B, a two-dimensional spatial localization of the individual objects within the xy-plane was possible. For example, the 0%-oil phantom (top left in Fig. 3A and B) was localized about 12 cm from the left border and 15 cm from the upper border of the scanning field.

Visual analysed, the signal-intensity decreased for increasing oil-concentration (Fig. 3B). According to Fig. 3B, the signal intensity of every phantom was compared and the values were normalized to the result for the 0%-oil phantom (blue curve of Fig. 3C). It can be seen that phantoms with low oil-concentration (0 - 30% (v/v)) and, correspondingly, with high permittivity values led to the strongest intensity of the backscattered signal (compare figures 3B and C with figures 2A and B), in accordance with the theoretical analysis of the reflection coefficient (black curve in Fig. 3C) and the visual analysis (Fig. 3B).

Images for this section:
Fig. 1: Spectroscopic results for nine oil-in-gelatine phantom samples with varying percentage of oil (from 0% to 80% oil (v/v)). A and B: Real part $\varepsilon'$ (Fig. A) and the imaginary part $\varepsilon''$ (Fig. B) of the permittivity of the phantom samples versus frequency. Error bars represent the standard deviation from an average of three individual measurements on the phantom surface. $\#'$ and $\#''$ of water and oil are shown as reference.
Fig. 2: Different images of nine oil-in-gelatine phantoms. A: Photograph of the position of the phantoms in the horizontal plain in the three-axis UWB-scanner. B: Image of the backscattered UWB signals of the phantom arrangement. The oil-concentration of every phantom is given in percent oil (v/v) in gelatine-solution. C: Comparison of the theoretical reflection coefficient of every phantom (black dotted line) and the measured backscattered signal intensity (blue dotted line) as a function of the oil-concentration.
Conclusion

In this study, nine phantoms were imaged in an arrangement on their particular dielectric values on the basis of ultra-wideband signals. The permittivity of the phantoms, as determined by dielectric spectroscopy, was in good concurrence with literature data [11], indicating that accurate reference values were used. Nevertheless, it is known that dielectric spectroscopy for UWB-imaging is an insufficient tool, because dielectric spectroscopy utilizing probes need direct contact to the material under test. Also the electromagnetic fields are decaying exponentially outside the probe, and the penetration depth of the waves into the material under test amounts to only a few millimetres, depending on the wavelength and the permittivity.

On the other hand, using a laboratory version of a three-axis UWB-scanner geometrical arrangement of phantoms could be recognized in a colour-coded image. Thereby, the signal intensity decreased for increasing oil concentration which showed good agreement with the corresponding reflection coefficients. These results demonstrate the possibility of discrimination of a dielectric material in heterogeneous backgrounds (Fig. 3B), particularly, in a physiological relevant permittivity range which is important for a clinical point of view to detect local differences of tissue water content.

However, these results represent a preliminary discrimination of the water content of coplanar localized tissues. Therefore, it must be regarded that a coplanar contrast depends also on the dielectric properties of the material arranged in front of the coplanar tissues. For increasing dielectric values \( \varepsilon_0 \), the contrast \( K \) increases according to

\[
\frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2} = \frac{\sqrt{\varepsilon_0 \varepsilon_2} - \sqrt{\varepsilon_0 \varepsilon_1}}{\varepsilon_0 - \sqrt{\varepsilon_1 \varepsilon_2}}
\]

where \( \varepsilon_1 \) and \( \varepsilon_2 \) is the permittivity of the coplanar tissues, \( \varepsilon_0 \) is the permittivity of the tissue in front of the coplanar tissues and \( \Gamma_1, \Gamma_2 \) symbolize the reflection coefficients. The potential of tissue discrimination inside the body is quite more relevant in terms of the envisaged applications in living organisms. In our measuring scenario phantoms adjusted
in air represent the worst case. Considering the dielectric difference ##\varepsilon = 3.65 \pm 2.15## between healthy tissues (#_1 = 46.13 \pm 1.80##) and cancerous ones (#_2 = 49.78 \pm 1.17##) as determined by Lazebnik et al. [13,14] for 5 GHz, the expected coplanar contrast should nearly be tripled for the case of fat tissue (assuming #_0 = 6##) compared to air (#_0 = 1##).

Besides to the determination of dielectric contrast, the signal-to-noise-ratio and the spatial resolution are important parameters of UWB imaging. The preliminary investigations in this study were carried out with a remote low-power prototype UWB imaging system and relatively large phantoms. Regarding the possible clinical applications of UWB in the long term, further developments and improvements of the imaging algorithms as well as the hardware parameters have to be made.

Our study demonstrates that it is feasible, in principle, to depict, identify, and localize different dielectric materials by electromagnetic UWB sensing. The results could pave the way for the use of UWB sensors in diagnostic radiology in the long term. Further work should be done to improve image reconstruction and contrast to allow a refined differentiation of the dielectric constant #\varepsilon - j\varepsilon''## of human tissues.