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UWB RADARS IN MEDICINE

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ABSTRACT

A review is given of present state of the art, and likely to be developed or futuristic, biomedical applications of Ultra Wide Band (UWB) radar.

UWB radar is something like a mix of conventional radar (RAdio Detection And Ranging) technology and spread spectrum radio (SSR) technology, both directly coming from military applications.

What renders UWB radar very much interesting is the possibility to probe the motion of the internal organs of the human body with a remote non-contact approach which is unique at present time. The very low cost, the high miniaturization capability and the environmental friendliness due to the very low electromagnetic energy emission are other aspects of specific interest of the technique.

A review of the biomedical applications known at present is presented based on the published documents and information derived from the web sites of the Institutions carrying on the research (gray literature). Just a paper only appears to have been published about the applications of UWB radar to actual medical problems, although many papers on the interaction of radio frequency energy with the living tissues, and safety issues, can be found in the literature.

An original and very simple model of UWB radar pulse-echo interaction with the human thorax is presented to show the feasibility of a real heart motion probe.

UWB radar technology, which is quite unknown at present time to the general public, and physicians as well, is about to strongly impact in everyday life and in the medical field as well, making it possible to design a novel kind of non-invasive measurement and monitoring devices.

KEYWORDS

UWB ultra wide-band, RADAR RAdio Detection And Ranging, Spread Spectrum, time domain, range gate, noise coding, SAR Synthetic Aperture Radar, SAR imaging, GPR Ground Penetrating Radar, foliage penetrating radar, optical radar, near-infrared spectroscopy, FDTD Finite Differences Time Domain method, pulse emitting antennas.

1. INTRODUCING UWB RADAR TECHNOLOGY

The overall conceptual working mode of a UWB radar system resembles that of ultrasonic echo transducers used in many applications, from *autofocus* cameras to proximity and range detectors. The main and fundamental difference being that, on the contrary to ultrasounds, electromagnetic pulses propagate through walls, ground, ice, mud, concrete and the human body as well.

Although many researchers around have been working on UWB technology for many years, a great concern on UWB radar arose in 1993 when it is reported that a Lawrence Livermore National Laboratory's (LLNL) engineer, Thomas McEwan, discovered a possibly new and original implementation of an UWB radar. While working on a new high speed low cost sampler for pulse laser research, McEwan developed a system which was called MIR: Micropower Impulse Radar. The patents on MIR technology describe a wonderful spectrum of applications coming from the low cost MIR technology: from plastic bodied mine detection, to remote vital signs monitoring, to the '3-D radar camera'. Of course the ultimate application being the futuristic 'X-ray specs' (until now just a science fiction device).

As a matter of fact the United States Patents and Trademark Office has recently rejected a few key claims of the MIR radar patent. Those claims were ruled as "anticipated", meaning previously claimed by Fullerton's 1987 Patent whose assignee is Time Domain Corp. Huntsville, Alabama.

Whatever should be the story regarding the intellectual property of the system, we are now interested, from the scientific point of view, on the biomedical applications of UWB radar which yet need a lot of research to get a viable, clinical oriented, device.

2. THE *RATIONALE* FOR BIOMEDICAL APPLICATIONS

Electromagnetic pulses coming from a UWB radar are able to probe the human body. In an application developed at LLNL, a UWB radar was able to detect, non invasively, the movements of the heart wall. This is because there do exist a definite difference in reflection magnitude between the heart muscle and the blood it pushes into the vascular tree. In the two patents ([1], [2]) awarded to McEwan on medical UWB radar, a rough description of the physical principle of operation is given. As the impedance of the cardiac muscle is in the order of 60 ohms and the impedance of blood is about 50 ohms, it can be expected a roughly 10% reflection magnitude of the radio frequency energy at the heart muscle/blood boundary. According to McEwan's patent, let μ_0 and ε_0 be respectively the permeability and permittivity of vacuum: the impedance of heart muscle is $Z_{(heart)} = \sqrt{\mu_0 / \varepsilon_r \varepsilon_0} = 60$ ohms, where ε_r is the permittivity of muscle (~40), while the impedance of blood (ε_r=60), is 49 ohms. The reflection coefficient, defined as (Y-1)/(Y+1) where $Y=Z_{(heart)}/Z_{(blood)}$, gives a 9.9% return fraction of the radiated pulse.

The same rule should be applied for reflection at air/chest interface or chest/lung interface and even at vessels boundaries.

The above model, proposed in the patents [1] and [2], is quite ingenuous as it does not account for the various living tissues which the incoming pulse has to travel before reaching the useful echo surface on the heart wall.

At the Tor Vergata University of Rome, Italy, we have recently studied a little more accurate model which considers thickness, impedance, linear attenuation and wave speed of six superimposed living tissues to be found by the UWB pulse while travelling through the human thorax from the skin to the heart.

The model is based on the data (Table 1) obtained from the Visible Human Project [3] and the Gabriel's data book of dielectric properties of tissues [4].

	impedance	attenuation	speed	thickness
	Ω	m^{-1}	m/s	m
air	376.7	0.00	$2.998\ 10^{8}$	$1.00\ 10^{-2}$
fat	112.6	8.96	$8.958\ 10^{7}$	$0.96\ 10^{-2}$
muscle	49.99	31.67	$3.978\ 10^{7}$	$1.35\ 10^{-2}$
cartilage	58.16	31.93	$4.628\ 10^{7}$	$1.16\ 10^{-2}$
lung	52.86	29.62	$4.206\ 10^{7}$	$5.78\ 10^{-3}$
heart	49.17	38.71	$3.912\ 10^{7}$	-

Table 1 – Electromagnetic and anatomical properties of tissue layers in the thorax.

The data allowed for the computation of echoes time delay along with the linear attenuation and reflection coefficients at boundaries.

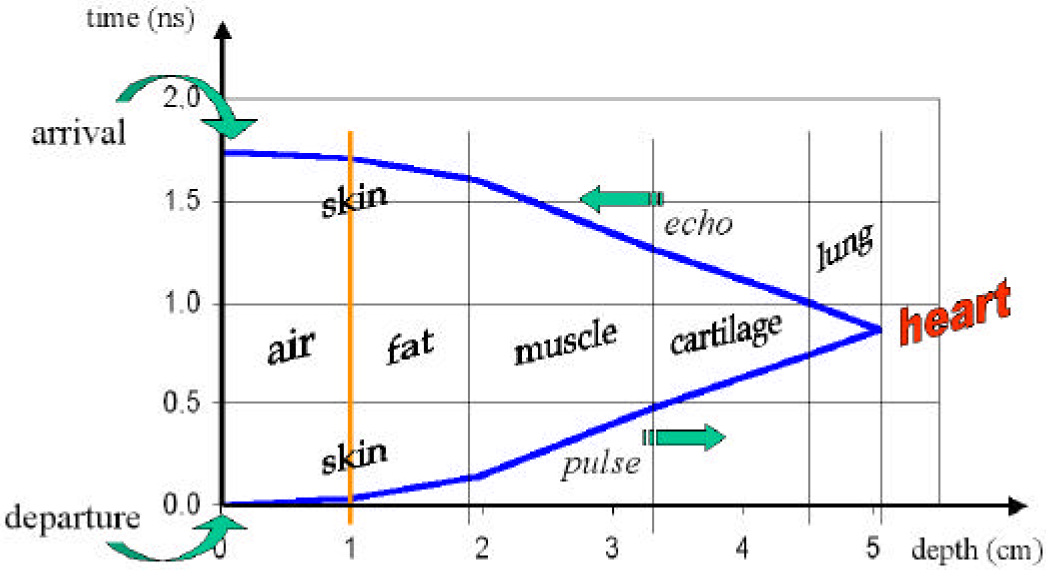


Fig. 1 – UWB pulse-echo delay times in the thorax as predicted by the model.

Although it seems more accurate from a physical standpoint, the new model of pulse-echo behavior in the thorax is all but correct at all. As the dielectric properties used were those measured on actual living tissues using a continuous wave at 1500 MHz [4], the model remains intrinsically wrong.

Indeed for an effective model to be developed, we need ultra wide-band dielectric properties, not narrow band ones (although in the microwave region). This means that a convolution method, or a Finite Differences Time Domain technique like that already employed in UWB antenna calculation [5], should be used.

Also, both the real part and the imaginary one of the reflection coefficients at the boundaries should be considered, this is because the UWB receiving correlator, working in the time domain, is, by design, strongly sensitive to phase errors.

Another point to be addressed is that of the receiving correlator itself. We need to assess what amount is actually its phase sensitivity.

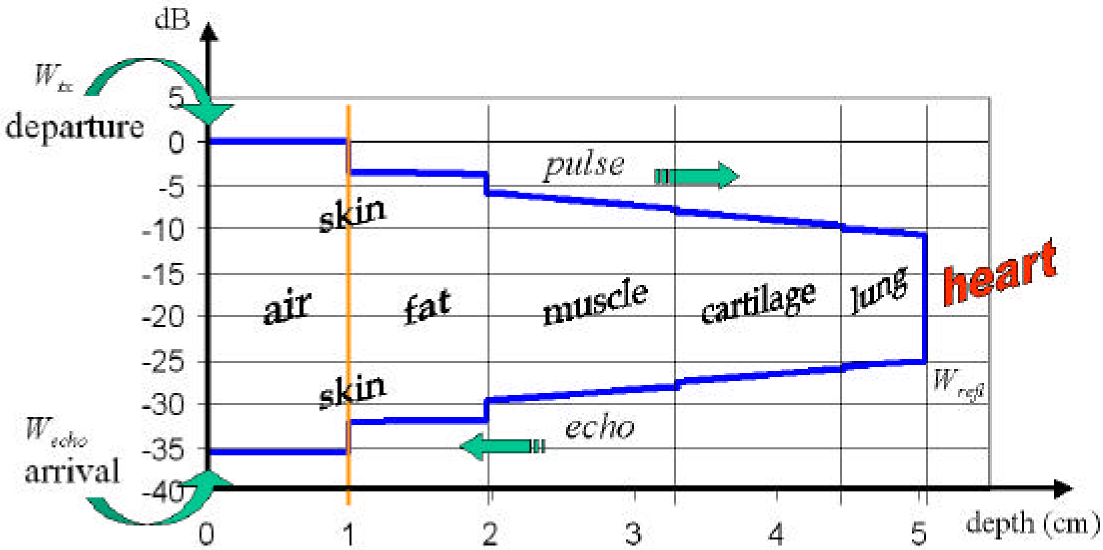


Fig. 2 – Model predicted attenuation of pulse-echo intensity travelling from the transmitting antenna to the receiving antenna. Each step accounts for echo at the boundary. Decreasing of the curve accounts for linear attenuation in the tissue (imaginary part of reflection coefficient and multiple reflections are ignored).

In a nutshell: we know that a heart motion-related signal is obtained out of a UWB radar device aimed at the thorax, but what are we actually measuring? To what extent correlator performances, pulse shape and tissues properties affect the intensity and morphology of the recovered signal?

These problems ask for some clear answers to reach an adequate physical understanding of medical UWB radar and subsequent clinical viability and acceptability of the technique. Accurate modeling of the phenomena with correct and extended electromagnetic measures should help advancement of science in this field.

This evidence opens up a whole new area for the non-invasive measures and monitoring of human body functions. In practice any object of adequate size can be monitored. Vocal cords, vessels, bowels, heart, lung, chest, bladder and fetus are good candidates for the UWB radar probing. As a matter of fact radar monitoring of human physiologic functions was considered as early as the 70's [6], [7], [8], but any further development was impeded by the cumbersome and expensive technology of those times.

But as long as human body monitoring is concerned, it has to be recognized that no other present time technology is using the same physical principle as UWB radar does. Furthermore no other system or methodology lets one monitor the movements of internal organs without direct skin contact and even using radiated, instead of induced, electromagnetic field. Functional magnetic resonance imaging (fMRI) is actually providing images of moving internal organs but, as it uses induced field, the patient has to be confined in space; while UWB radar, using radiated field, lets the patient be absolutely free in space. No other direct comparison is to be made between UWB radar and fMRI, as the purpose and final clinical target of the two methodologies are far too different.

Fig. 3 – Actual slice of the thorax from the Visible Human Project. Chest is on the low part of the image; U-shaped left ventricle section is at center right. The layers of living tissues are seen from the chest to the heart: skin and fat (yellowish), muscle (red), cartilage (reddish), lung (red) and the heart wall (red). Pericardium is visible at lung/heart boundary.

The somewhat "magic" performances of UWB radar technology might be summarized in a futuristic ultrasound-like apparatus able to gather images (or at least scalar measures or simple 'monitoring') of the internal organs of the human body without direct skin contact nor precise positioning. New systems could be able to even work through clothes or blankets and at a distance up to ten or more feet. With proper research and funding this scenario is probably just five years away.

Many medical applications of this new technology are about to be developed in the near future provided a large research work be done form the engineering and medical point of view. Due to the extremely high and profitable industrial interest, this field of research is expected to have a huge funding both from governmental agencies and private companies as well.

3. THE BIOMEDICAL APPLICATIONS OF UWB RADAR TECHNIQUE

By using a particular non-resonating antennas (to avoid ringing), the MIR was operated as a cardiovascular monitor to detect cardiac contractions, arterial wall motion and a breath monitor to detect respiratory movements.

Furthermore MIR system, used as electromagnetic sensors (EM-sensors) are experimented for assessing vocal cord activity and speech parameters.

The use of the UWB radar in cardiac motion evaluation is a wonderful complement of the electrocardiogram (ECG) as a cause-effect pair. More interesting to physicians would be the relationship between UWB radar heart tracings and what MDs already know very well: the M-mode echocardiogram which uses ultrasounds.

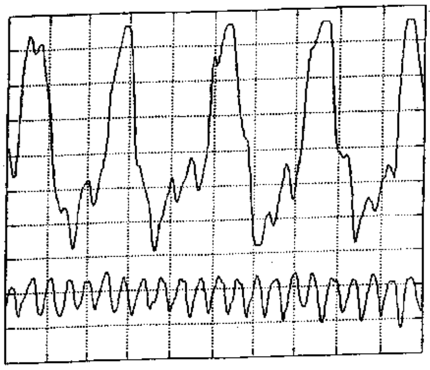


Fig.4 - Upper trace: mean echo power coming from the thorax (the respiratory activity is strongly overwhelming the heart movements). Lower trace: same with respiratory activity stopped (apnoea). Horizontal units: 2 secs/div. Vertical units: arbitrary. Drawing obtained from U.S. Patent n. 5,573,012.

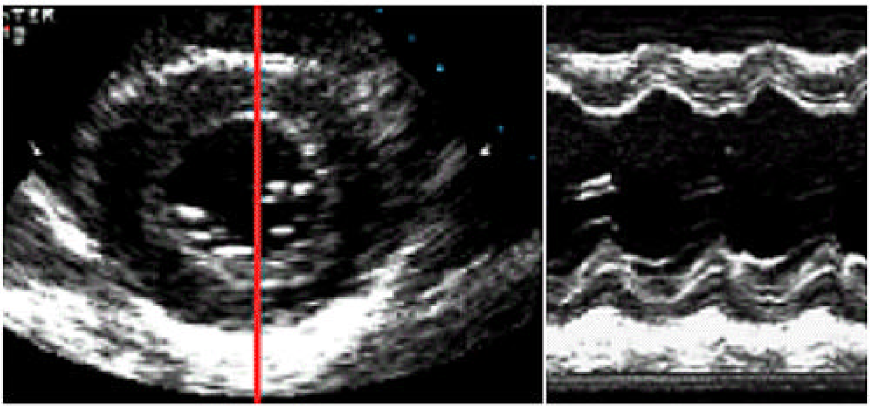


Fig.5 - Two-dimensional echo (short axis view) showing the left ventricle and the corresponding M-mode tracing (along the red line of scan). In theory *(we hope?)* a relationship should exist between the lower tracing of Fig.4 and the right part scan in this figure.The main question with UWB echocardiography is: what are we looking at?

As the UWB electromagnetic signal is not influenced by clothes or blankets and the useful range is in the order of a few meters, a through-clothing heart rate monitor is viable so that interesting potential applications can be envisioned. Home health care, emergency rooms, intensive care units, hospitals, pediatric clinics (to alert for the Sudden Infant Death Syndrome, SIDS), rescue operations (to look for some heart beating under ruins, or soil, or snow) or law enforcement are just some of potential areas of application.

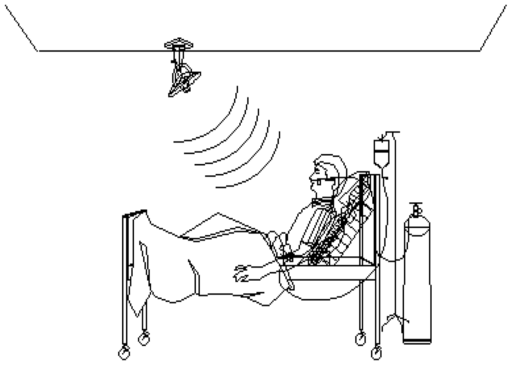


Fig.6 - A straightforward application of UWB radar-based heart and breath activities is shown for intensive care units (ICU) and conventional hospital beds as well.

Tracings of arterial pulsation have been obtained too. This is an area of research deserving further attention. As arterial wall motion is related to internal pulse pressure an arterial pulse pressure monitor should be obtained. By monitoring pressure pulse on two different sections of an artery a pulse pressure speed measurement (celerity) could be obtained. Please note that pulse pressure celerity is much higher than actual blood speed into the vessel. It is already known that blood pulse pressure speed is directly related to vessel wall visco-elastic properties. A non-contact, non-invasive method for celerity measurements would be a real breakthrough as a diagnostic tool for arterial diseases as arteriosclerosis.

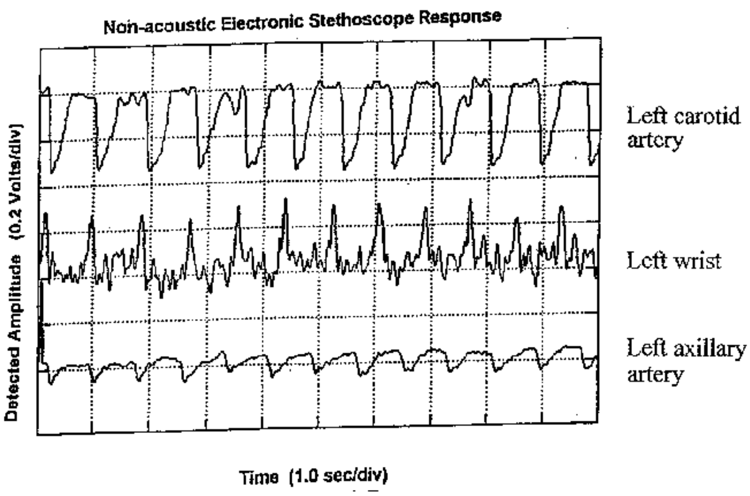


Fig.7 – UWB radar-based exploration of arteries.
Drawing obtained from U.S. Patent n. 5,573,012.

A really sound application of UWB radar in the medical field is that depicted in Fig. 8. UWB radar emissions are safe and therefore the system is very well suited for a chronically positioned equipment to monitor the last period of pregnancy or to assist in evaluating labor progress. The "obstetric UWB radar" will require proper microprocessor control of range gating and a quite accurate signal processing to extract the various data out of the echo signal.

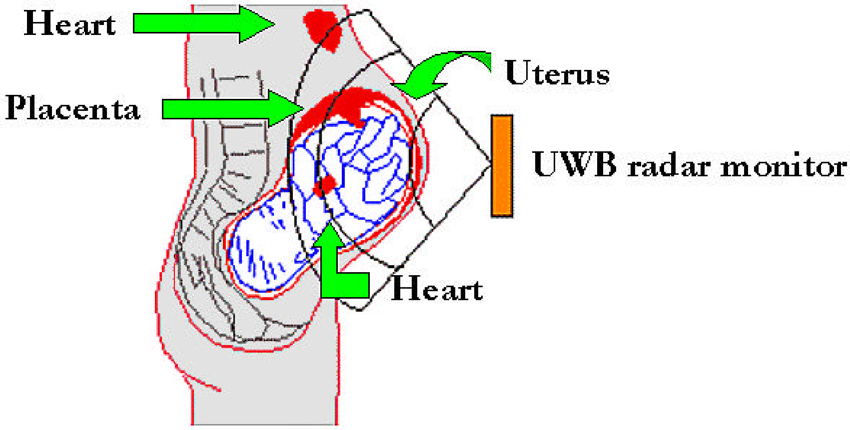


Fig.8 – An UWB radar could replace presently used fetal monitors which use ultrasound (to detect placentary blood flow) and pressure sensors (to detect uterine contractions): the UWB radar signal contains data about maternal heart rate, maternal breath rate, fetal heart rate, fetal movements and uterine contractions as well. Furthermore the remote, non-contact, non invasive operation permits conventional, uninterrupted, mother and child care.

Speech assessment and monitoring of living structures involved in phonation has been recently addressed by some researchers at Lawrence Livermore National Laboratory (where the "radar microphone" was developed), at the University of California Davis and at the University of Iowa [9]. Work is in progress toward a better understanding on how humans produce speech. Furthermore information has been gathered for speech recognition, speaker verification and speech synthesis.

Probably, from the technical standpoint, the most interesting feature of this device lies in its very low cost and ease of production. Even if this system mainly works in the microwave region, it can be built from off-the-shelf electronic components and no particular adjusting or special cavities or striplines are needed. A breadboarded, amateur version, working somewhere near 800 MHz, was developed (just to see the magic in it) at the University of Rome "La Sapienza" in a collaboration between the Centre for Biomedical Engineering and the Electronic Engineering Dept. of the same University.

The only critical component being the antenna which, for many practical applications, has to be non-resonating: in general a quite complex problem [5]. Of course, as you may imagine, no resonant circuit should be included in an ultrawide band system.

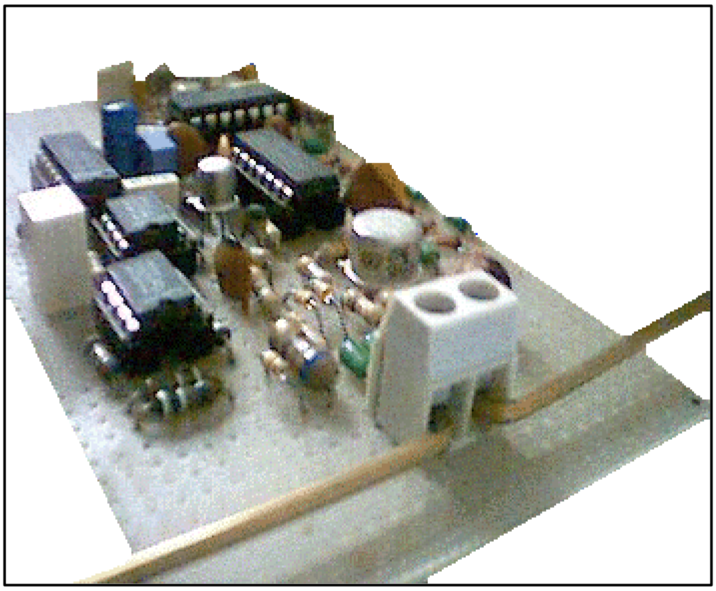


Fig.9 – The UWB radar prototyped at “La Sapienza” University of Rome in 1998. This bread-borded version works near 800 MHz, uses commercially available components available at radio stores and detects heart and body movements. A very simple (resonating!) dipole was used.

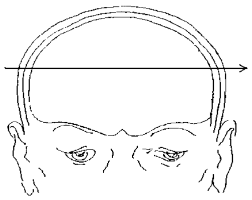
Low end consumer products based on UWB radar technology could reach as low prices as a couple of US dollars in the near future.

For biomedical applications, a couple of watt peak power pulses suffice and, considering the very low duty cycle, the mean emitted power is in the order of tens of microwatt. This power level is so weak as to be considered intrinsically safe for humans. As a consequence no harm will derive to patient even in chronically operated monitoring. Many studies have already been published regarding the effects of animal and human exposure to ultra-wideband radar emissions [10], [11], [12], [13], [14], [15]. Furthermore battery operated devices are expected to have a huge working time between battery replacements.

4. AN OPTICAL UWB RADAR

What if the receiving-transmitting antenna is replaced by a laser-diode and photo-diode pair? An optical UWB radar results!

Instead of emitting a short electromagnetic pulse a short train-wave of light (electromagnetic energy as well) is emitted and the echoes detected by a very fast PIN photodiode. Resulting biomedical applications are quite interesting.



It is well known that the skull and the brain are in a somewhat transparent to infrared (IR) energy. IR transmission spectra of the whole brain are being used to investigate brain metabolism and blood circulation, especially in the newborns.

Using UWB radar based systems the same studies could be performed with a time-resolved technique (not just lock-in) enabling IR imaging of sectors of the brain *in-vivo* and non-invasively with better results.

Of particular interest could be the estimation of hemoglobin oxygen saturation in selected brain districts. The UWB radar-adapted, otherwise well-known, method of oxygen saturation monitoring could be used.

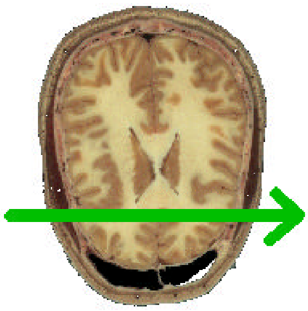


Fig.10 – Possible beam path drawn on a real anatomical section image of the head (image obtained from the Visible Human Project).

5. CONCLUSIONS

The applied research on biomedical applications of UWB radar will be targeted to the identification of the possible new devices made possible by the technology, to the design and development of those devices and to the clinical testing of the systems obtained. Applications can be divided into two main sectors according to the frequency range used in the UWB device.

For the conventional UWB radar microwave region, the devices could be listed for:

- cardiac biomechanics assessment
- chest movements assessment
- OSA (obstructive sleep apnoea) monitors
- soft-tissue biomechanics research
- heart imaging (‘Holter type’ echocardiography)
- chest imaging

along with systems for:

- cardiac monitoring
- respiratory monitoring
- SIDS (sudden infant death syndrome) monitors

- vocal tract studying

If an IR laser diode is used as the antenna, a more common radar is obtained (actually an hybrid between a narrow band and a wide band radar) which emits a short packet of electromagnetic waves whose echoes are sampled using a ‘conventional’ UWB receiver equipped with a PIN photodiode. A series of possible devices can be listed for the IR region:

- non-invasive biochemical study of soft tissues (exp. brain)
- non-invasive study of metabolic processes
- IR spectral imaging.

Let’s conclude with a dream: that of non-invasive, continuous (Holter-type), monitoring of cardiac output. With acceptable limitations, it could be in fact possible by measuring, with an UWB radar, the difference in distance between the anterior and posterior left ventricle walls. This could give an estimation of ventricle’s volume variations during the heart cycle and eventually give systolic ejection volumes and cardiac output. With the rapid technology advancements we are experiencing these times, it only needs to have a dream for that becomes true.

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