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STSM Technical Report: Experimental evaluation of a microwave sensor performance on pneumothorax diagnosis

COST Action: *COST EMF-MED (Action BM1309): European network for innovative uses of EMFs in biomedical applications*

Young Researcher: *Dr. Maria Christopoulou*

Home Institution: *University of Patras, Greece (Contact person: Assist. Prof. Stavros Koulouridis)*

Host Institution: *IT'IS Foundation, ETH, Zurich, Switzerland (Contact person: Prof. Niels Kuster)*

STSM Reference: *ECOST-STSM-BM1309-101114-051293*

STSM dates: *from 10-11-2014 to 05-12-2014*

Purpose of the STSM:

As described in the STSM application, STSM objectives focused on the experimental assessment of the printed antenna sensor diagnostic performance, while operating onto a modified chest phantom. The experimental study was considered essential in order to verify the numerical simulation findings. Therefore, the STSM objectives were twofold: i) numerical modeling and implementation of a chest phantom including lungs while given quantity of air is inserted in order to model pneumothorax, and ii) experimental evaluation of the diagnostic performance of the sensor, while operating onto the implemented thorax phantom.

Work Description:

The research work implemented during the STSM is analysed day-by-day in the attached time report of Dr. Maria Christopoulou. More in detail, the research work is structured into three parts:

A. **Week one: Numerical design/modelling of the thorax experimental phantom and tissue liquids:** During the first week, Maria had meetings with her colleagues from IT'IS Foundation, in order to discuss and finalise the design and the customised solutions for the experimental phantom. Some ideas were discussed about a first simplified solution of the phantom in order to represent a section of the biological tissues from skin to lung, during healthy and pneumothorax cases. The final solution that was decided was the implementation of two separate containers: one made of skin (5 mm) and fat (15 mm) and another one made of lung (160 mm). In front of the skin layer, a plastic cover was decided to be placed in order to protect the skin material from sagging (due to the filling of the container with liquid). Two windows would allow the antennas to be placed onto the phantom and being in touch with the skin. The two containers will be separated by two sheets of FR4 (1 mm each). In between these sheets, Styrofoam layers of different thicknesses will be placed in order to represent the trapped air layer during pneumothorax. Styrofoam was selected because it is 'invisible' to microwaves. Additional simulations were prepared in order to assess the influence that the two FR4 sheets could have in the pneumothorax detection and the distinction between the two cases. Moreover, along with a colleague from IT'IS, Maria made a comparison between the dielectric properties of the materials used in the simulations, based on Gabriel's database and the available recipes for liquids by IT' IS, in order to conclude about the closest ones, which will be used in the experimental measurements. Maria was also trained in using the DAKS-3.5 for dielectric properties measurements. DAKS-3.5 is a low cost, portable, and easy-to-use dielectric assessment system kit that combines the DAK-3.5 technology with the miniature portable R140 vector reflectometer from Copper Mountain Technologies. Measurements of the semi-solid material that was used for dry skin were conducted by Maria, following the foreseen protocol for semi-solid materials. Measurements data were compared to SPEAG and simulations database. The materials (semi-solids and liquids) to be selected for the phantom were finalised. Last, Maria contacted with the Medical Doctor in Greece, in order to finalise details about the medical case representation.

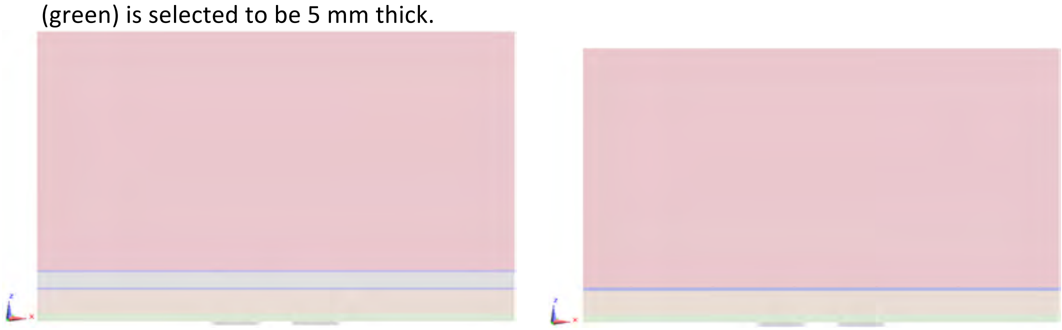
B. **Week two and three: Measurements of the tissue liquids/Optimisation of the recipes:** The first day of the second week, Maria verified with Bruno Reumer (Head Production) the final model of the phantom in order to start its production. It was decided to open wider windows in front of the skin in order to cover more future applications of larger antennas. The production would take almost two weeks. Additional simulation scenarios were prepared in order to verify whether given changes in the phantom construction could influence the detection ability of the dual antenna sensor. Such changes were the thickness of the lung, its modelling as deflated or inflated, the fat modelling as infiltrated or non infiltrated, the grid, the voxel size, the frequency range, the harmonic or broadband simulation. Waiting for the phantom construction, Maria proposed to experiment herself with the liquid recipes, in order to optimise the infiltrated fat dielectric properties. Therefore, Maria had plenty of discussions with Fin Bomholt (Director Research and Development) in order to familiarise herself with the liquid testing time-consuming procedure. In total, 16 recipes were made and measured with the DAKS-3.5. All the recipes were based on four different chemical components, used in-house at IT'IS and changes in relative permittivity and conductivity were attempted, by using different proportions of de-ionised water and salt. This procedure proved to be very sensitive to component quantities, stirring procedures (some recipes resulted to gelly mixtures) and temperature. In order to stabilize the temperature of the samples to be measured, a water-bath was constructed and it was kept in controlled lab temperature. At the end of the third week, Maria and Bruno made a tentative quality check for the phantom in order to verify that there is no leakage of liquid when the two phantom containers are full and there is no sagging in skin material and FR4 sheet, because of the liquids pressure. The check proved that phantom could be used for measurements during the fourth week. Last, administrative paper work was also done in order to prepare the documents for the shipping of the phantom and the corresponding liquids.

C. Week four: Measurements of S_{11}, S_{12}, S_{21}, S_{22} of the dual sensor, placed onto the phantom for different scenarios: Maria filled the phantom with the liquids and a small gap (less than 0.5 mm) between the two FR4 sheets was noticed. Therefore, additional simulations were prepared in order to assess its contribution to the air detection ability of the dual antenna sensor. Simulations with the final set-up with air thickness of 5 mm, 7 mm, 10 mm, 20 mm, 30 mm with inflated and deflated lung, were also prepared. Maria along with Myles Capstick (Associate Director) prepared the measurement set-up, calibrated the VNA, selected the cables for the antenna feeding, used a water-based gel in order to stabilize the matching between the antennas and the skin material, constructed a set-up to stabilize the antenna pressure onto the skin, cleared the soldering of the antennas in order to minimize the in-between air gap and finally stabilised the S_{11}, S_{12}, S_{21} and S_{21} parameters, in order to derive reproducible results. The antennas S_{11}, S_{22} were measured in free space and onto phantom and these parameters were compared to the simulated data. Measurements of the S_{21}, S_{12} parameters for healthy (0 mm of air, inflated/deflated lung) and pneumothorax (2, 5, 7, 10, 20, mm of air, inflated/deflated lung) cases were conducted and compared to the simulated data. The liquids change was proved to be time-consuming procedure, due to the high viscosity of some liquids. The final cleaning of the phantom was completed the last day of Maria's visit.

<u>Main Results:</u>

Based on the above mentioned work description structure, the main results of the STSM are summarised as following:

A. Concerning the phantom design, Fig. 1 illustrates the numerical model of the final design, representing the two scenarios: (a) pneumothorax of 10 mm of air (grey) and (b) healthy case. The lung (dark pink) is modelled as deflated in pneumothorax, due to the pressure of the lung and as inflated in healthy case. The two FR4 sheets are modelled as blue 1 mm sheets (blue). Fat (light pink) is modelled as infiltrated fat since this form of fat is more common in reality. Additionally, the thickness of fat was selected in order to model the worst case scenario. Last, the bones were not modeled since the dual antenna sensor is intended to be used in the intercostal space (between the ribs). Skin layer (green) is selected to be 5 mm thick.



X: *300 mm*
Y: *300 mm*
Skin: *5 mm*
Fat: *15 mm (infiltrated)*
FR4 low: *1 mm*
FR4 high: *1 mm*
Lung: *160 mm*

(a) (b)

Figure 1: Numerical representation of the last version of the phantom in both medical cases: (a) pneumothorax of 10 mm of air thickness and (b) healthy case.

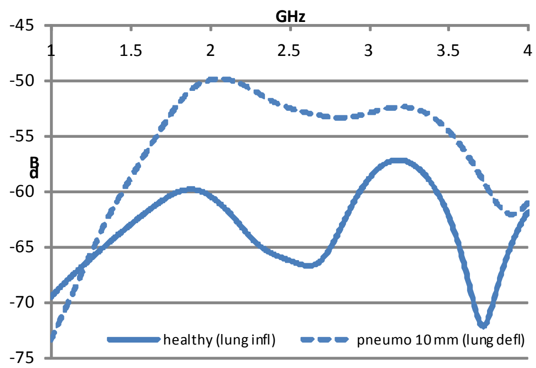
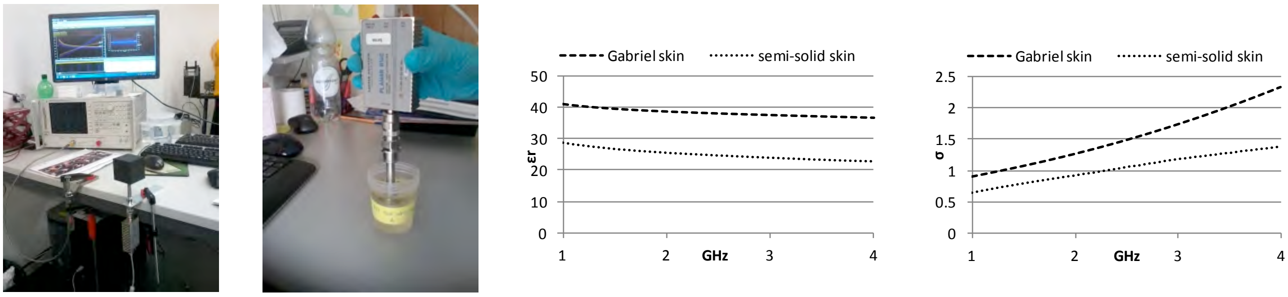


Figure 2: S_{21} variation plot for healthy and pneumothorax cases (simulated data).

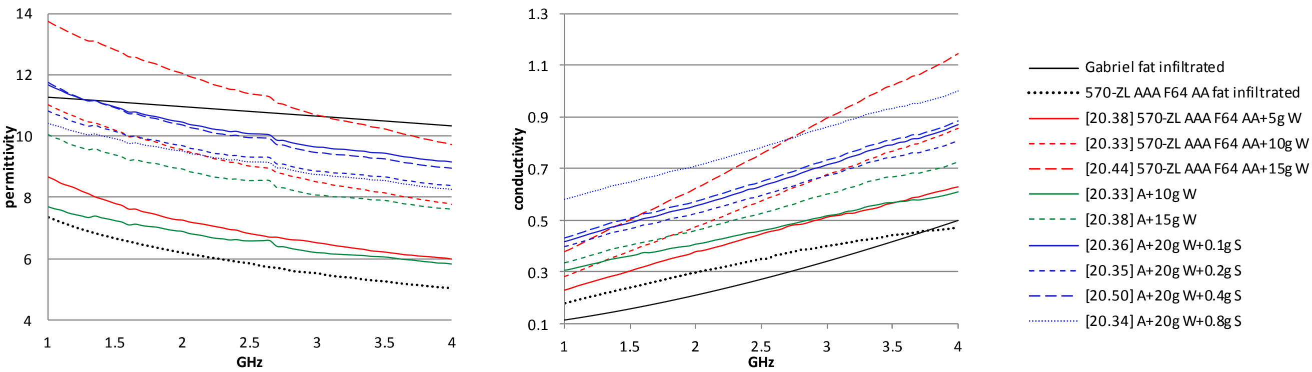
Figure 2 illustrates the plot of the S_{21} variation simulated for healthy case with inflated lung and pneumothorax case of 10 mm air with deflated lung. In both simulations, the same grid has been used, as well as the final liquids/materials to be used in measurements. The difference between the two cases reaches 13 dB at 2.6 GHz. Additionally, the dielectric properties of the skin semi-solid material were measured, using the DAKS-3.5 (Fig. 3(a)) at 1-4 GHz frequency range. Please note that for the selected liquids used for infiltrated fat, inflated and deflated lung representation, the same procedure was followed for the measurements (Fig. 3(b)). The measurement results compared to the simulated ones, based on the Gabriel's database and the comparison plots are summarised in charts of Fig. 3(c-d) for semi-solid material representing skin. The same procedure was followed for the liquids used for the phantom, but for brevity reasons only comparison for skin material is presented.



(a) (b) (c) (d)

Figure 3: Measurements procedure using DAKS-3.5 for (a) skin semi-solid material, (b) liquids. (c) Permittivity and (d) conductivity values dispersion of the skin semi-solid material in the frequency range of 1-4 GHz.

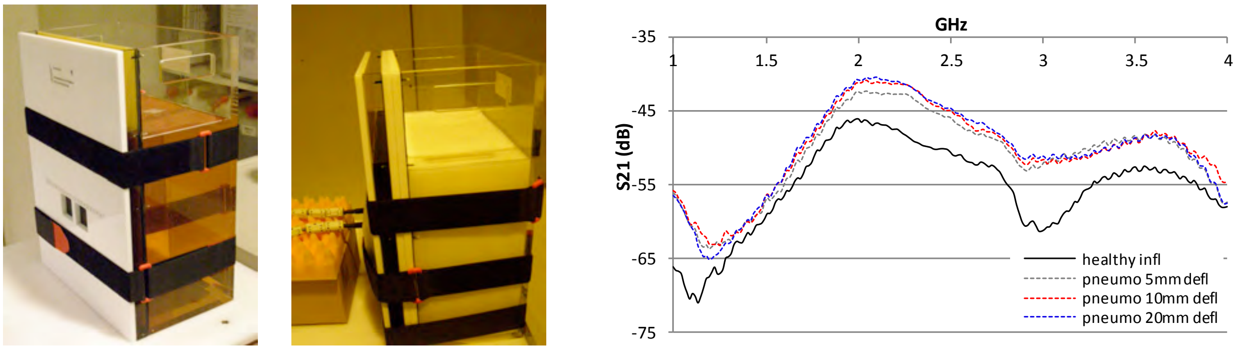
B. Concerning the optimisation of the infiltrated fat liquid recipe, in total, 16 recipes were made and measured with the DAKS-3.5. All the recipes were based on four different chemical components, used in-house at IT'IS and changes in relative permittivity and conductivity were attempted, by using different proportions of de-ionised water and salt. The results are summarised in Figure 4. More details about the chemical that were used cannot be provided, due to protection of the in-house recipes. For brevity reasons, measurement results only for eight recipes, compared to Gabriel database and the in-house recipe 570-ZL AAA F64 AA that was used for infiltrated fat, are illustrated in Figure 4. Three (3) recipes were based on the 570-ZL AAA F64 AA liquid by adding de-ionised water (W) and five (5) were based on another chemical component A, by altering the proportion of de-ionised water (W) and salt (S). The measurement temperature was kept almost stable varying from 20.33-20.50 ^{0}C. Figure 4 illustrates the relative permittivity (Fig. 4(a)) and conductivity (Fig. 4(b)) dispersion of the proposed recipes within the frequency range of 1-4 GHz, compared to Gabriel database and 570-ZL AAA F64 AA liquid measurements. The samples temperature is mentioned in blankets ('[]'). The main conclusions from the recipes trials are the following: Concerning the 570-ZL AAA F64 AA liquid, the water increase results to the inevitable increase of permittivity but, at the same time the conductivity increases far away from the target values. The same trend is noticed for the water increase to the A chemical component. Last, the combination of water and salt proportion in the A chemical cannot lead to a straight forward trend for permittivity and conductivity, since the proportion of these two ingredients, the temperature and the stirring conditions seemed to influence significantly the trend of the dielectric properties dispersion, within the frequency range of 1-4 GHz.



(a) (b)

Figure 4: (a) Relative permittivity and (b) conductivity dispersion within the frequency range of 1-4 GHz for eight selected recipes in comparison to Gabriel database and the in-house recipe 570-ZL AAA F64 AA that was used for infiltrated fat.

C. During the last week of the STSM, Maria checked the quality of the thorax phantom with and without the air spacers. The quality check was made using first water and then the chosen liquids for the biological tissues representation. Figure 5 illustrated the implemented phantom, filled with selected liquids, corresponding to healthy case (Fig. 5(a)) where the lung container is filled with inflated lung simulating liquid and pneumothorax case of 20 mm air thickness (Fig. 5(b)) where the lung container is filled with deflated lung simulating liquid. Figure 5(a) illustrates the two windows of 40x40 mm^2 opening each, where the two antennas will be placed onto the skin layer, while the set-up selected in order to stabilize the antennas pressure and separation distance onto the skin layer is illustrated in Figure 5(b). The measurements series that were tested are: i) healthy case with inflated lung, compared to ii) pneumothorax case with 2, 5, 7, 10, 20, 30 mm of air thickness with deflated lung. Figure 5(c) illustrates the S_{21} amplitude variation in dB in frequency range of 1-4 GHz. The difference between healthy and pneumothorax (5 mm) cases reaches 10 dB at 3 GHz. As the air thickness increases, the S_{21} difference increases as well, but this change is not considered significant, which is verified by the corresponding simulation results, as well. Last, comparing to simulations, there is a 400 MHz shifting of the two S_{21} drops to higher frequencies, with can be justified by the inevitable air gap (~ 0.5 mm) between the two FR4 sheets and other construction reasons.



(a) (b) (c)

Figure 5: Implemented thorax phantom (a) healthy case where the lung container is filled with inflated lung simulating liquid, (b) pneumothorax case of 20 mm air thickness where the lung container is filled with deflated lung simulating liquid. (c) S_{21} variation within the 1-4 GHz frequency range for healthy and pneumothorax cases for air thickness of 5, 10 and 20 mm.

Future collaboration:

Further collaboration could be planned in future for the implementation of an anatomical thorax phantom, using 3D printer molds and gel/semi-solid materials in order to form the curvature of the anatomic torso and lungs. This could be interesting for both parties.

Foreseen publications/articles:

At least two (2) publications/articles will be prepared: one announcement in international scientific conference (such as BioEM 2015 in USA) and one journal paper.

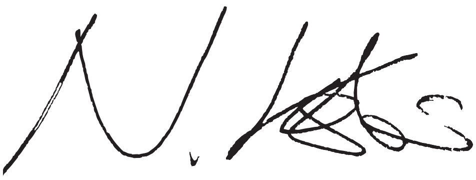
Confirmation of the host institution:

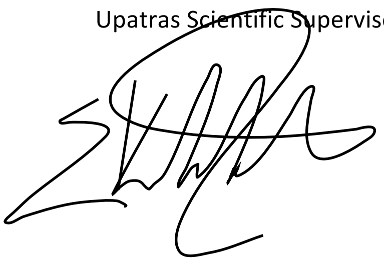
We confirm that Dr. Maria Christopoulou has performed the research work as decribed above. The time available was not sufficient to complete the work due to the production time needed to build the phantom but the most important objectives were achieved such that the final quantitative validation can be completed at the University of Patras.

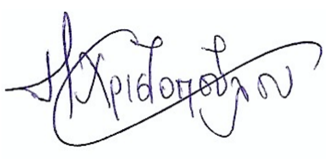
Comments:

Additional points to be highlighted: The foreseen time of the STSM was proved to be marginal or even short for the amount of research work that was scheduled to be done. However, the first row of measurements was completed during the last week. Moreover, it was very positive that Prof. Niels Kuster agreed to ship the phantom along with the liquids to University of Patras which facilitated the further evaluation of the dual patch sensor and the assessment of other antenna sensors.

IT IS Scientific Supervisor | Upatras Scientific Supervisor | Young Researcher







N. KUSTER | ST. KOULOURIDIS | M. CHRISTOPOULOU