Development and experimentation of atelemedicine solution built around a digital stethoscope. The "BlueHealth" project

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Abstract— *In this paper, we assess the viability of a solution using a digital stethoscope, together with cordless Bluetooth technology for the comfort of use and the telecommunication means and technology to offer a cost / performance ratio that makes it applicable to Doctor markets (eStetho).We also assess the development of a telemedicine solution: BlueHealth project, in relation with this electronic stethoscope. The described solution allows for: 1) Collection, cleaning and record of physiological data in streaming mode; with primary focus on auscultation sounds for lung and heart analysis; 2) Formatting xml based metadata to carry administrative information related to the patient, to the practitioner, to the device, to the institution, etc., together with physiological data; 3) Transmission of data (protection, confidentiality, access rights, sharing, etc.); 4) Processing (signal processing) of the data for diagnostic help; and 5) Multimedia communication, with audio over IP and display of the record on IPTouch or any other xml compatible device.*

Keywords— Telemedicine; Auscultation; Stethoscope; Use case; Bluetooth.

Authors contributions— This work was carried out in collaboration between all authors. Authors EA, SR and RG designed and wrote the project. Authors EA, SR and RG managed the development of the project and the experimentation. All authors read and approved the final manuscript.

I. INTRODUCTION

Auscultation of a patient's heart or lungs is part of the Doctor's professional services [1]. The stethoscope is the emblem of medicine, and yet the tool is of rather poor quality, and the assessment cannot be made remotely. Remote auscultation would improve patient follow-up and clinician-patient interaction. An electronic stethoscope together with signal processing algorithms inherited from the telecommunication world such as echo cancellation, noise suppression, and voice activity detection will make it easy to provide objective analysis of auscultation records and facilitate teaching auscultation [2].

To date, current inhibitors to the widespread deployment of electronic stethoscopes mainly reside on the price (range of $200 to $800), and on quality problems (not solve properly the problem of ambient noise and noise introduced by the sensor head).

In this paper, we assess the viability of a solution using a digital stethoscope, together with cordless *Bluetooth* technology for the comfort of use and the telecommunication means and technology to offer a cost / performance ratio that makes it applicable to DoctorMarkets (eStetho).

We also assess the development of a telemedicine solution: *BlueHealth* project, in relation with this electronic stethoscope.

II. AUSCULTATION

Acquisition and analysis of human sounds are the basis of heart and lung medical examination [3]. Auscultation opened the door and helped developing clinical disciplines by identifying heart and lung semiology. Studies on diagnostics establishment out of the "subjective" listening of sounds provided by stethoscopes have decreased over the last 20 years, with the advent of functional exploration techniques such as medical imaging.

Heart auscultation assists in identification of correct heart rhythms and the detection of abnormal sounds or murmurs that indicate possible myocardium, valvular or pericardial pathology. Lung auscultation has been the basis, for years, of Pneumology, before medical imaging, in particular X-ray examination.

Thanks to signal processing technologies, the status of auscultation may be improved, with better diagnostic performance, objective tools for medical education, second opinion, follow up of pathology evolution, and the creation of an auscultation sounds database to support medical research [2,4].

III. STETHOSCOPE IN THE MARKET

Invented in 1816 by René Laennec, the first versions of the single ear stethoscope replaced the practice of mediate auscultation (the Doctor directly applies his ears against the chest of the patient) (figure 1) [1,5].

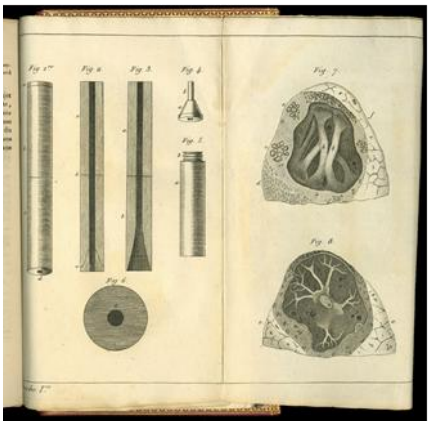

FIGURE 1: LAENNEC'S STETHOSCOPE

The stethoscope evolved slowly during the 19th and the 20th centuries, to become in most cases a binaural tool [5]. They are usually made of Y-shaped rubber tubing that acts as a wave guide to allows sounds to enter the device at one end, travel up the tubes and through to the ear pieces. The sound-detecting device is either a two-sided head that listeners can reverse, (depending on whether they need to hear high or low frequencies) or a one-sided pressure-sensitive head. Differential stethoscopes allow listeners to compare sounds at two different body sites.

More recently, electronic stethoscopes went on the market that makes use of a microphone in the head plus amplifier and filters to mimic the two-sided head of a traditional stethoscope [5]. The major drawback with these electronic stethoscopes is that interference and noise mask useful sound sequences and may prevent the physician from detecting patterns that are significant on a clinical basis (figure 2).

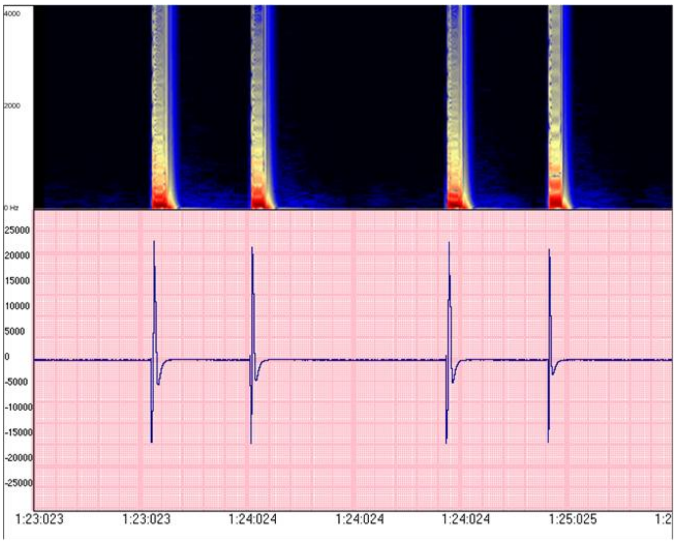

FIGURE 2: ELECTRONIC STETHOSCOPES OF THE MARKET: NICE PICTURES, BUT DANGEROUS TOOL.

It is therefore essential to: 1) Discriminate between noise and useful information; 2) Provide sound amplification that fulfils the dichotomy of providing sound integrity to automatic sound recognition algorithms for help in diagnosis (detection of crackles, wheezes, heart murmurs, …), whilst rendering sound characteristics that are familiar to the medical practitioners; and 3) Cancel ambient noise.

IV. DEVELOPMENT OF A PROTOTYPE OF INNOVATIVE DIGITAL STETHOSCOPE: *ESTETHO*

Initial surveys about acceptance of a digital stethoscope, together with efficient means to cancel noises and provide signal analysis to help diagnostic establishment, show a strong interest from countries where trip costs may be eliminated by providing real-time or time-deferred remote patient assessment.

In this context we have developed a communicative and intelligent electronic digital stethoscope (figure 3). Part of these developments has been conducted in collaborative projects between *Alcatel-Lucent* and the University Hospital of Strasbourg (in Strasbourg, France). The two main projects are the *STETAU* ("*Stéthoscope*", grant from the *Direction Générale de l'Entreprise*, 2005) and *ASAP* ("*Analyse des Sons AuscultatoiresPathologiques*", grant from the *AgenceNationale de la Recherche*, 2006)projects designed in the framework of the national program from the French Government to promote translational research [6,7].

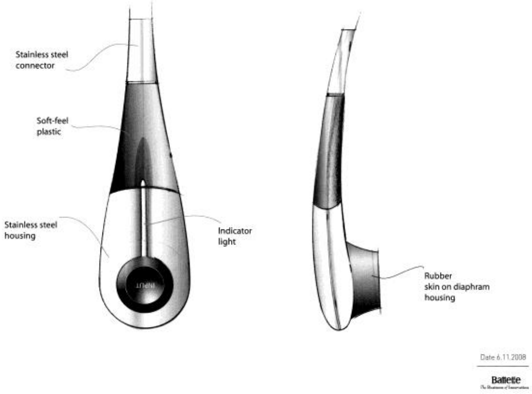

FIGURE 3: PROTOTYPE OF INNOVATIVE DIGITAL STETHOSCOPE

The objectives of these research projects will consist in the implementation of a *Bluetooth* electronic stethoscope, together with signal processing and data communication techniques [6,7]. The objective being to improve quality and decrease costs as compared to existing electronic stethoscopes.The second step will be the connection of additional *Bluetooth* enabled sensors to allow for multiple synchronous analyses (e.g. heart auscultation together with ECG to eliminate artefacts and improve the accuracy of the diagnosis).

The prototypes of our digital stethoscope (*eStetho*) have been experimented at the University Hospital Strasbourg (October 2013) [4]. The prototypes are used to monitor patients and to facilitate interaction between healthcare professionals. *Bluetooth* connectivity inside the hospital, together with mobile voice over *WiFi* technology will offer integration with a hospital patient database of auscultation records that enables real-time visual representation of auscultation sounds for second opinions or for training courses [6-8].

We also spent a large part of our developments to promote researches on auscultation and education through this new tool. In addition, the lung and heart sounds that have been collected will be used for new research programs with the goal of identifying specific markers that are not yet known because they were not accessible to human ears. Medical Universities also showed interest in setting up new, objective material for teaching auscultation.

The proof of concept that was developed so far includes [8]:

- An electronic stethoscope offering *Bluetooth* connectivity that covers the [10 Hz – 4000 Hz] frequency range;
- Various stethoscope mechanics have been tried to provide the ergonomics that is familiar to medical experts;
- The microphone and the loudspeakers of the handset are integrated inside the head of the stethoscope;
- Visual representation of the time and frequency characteristics of the signal are represented during auscultation and afterwards for analysis;
- Applications have been developed, based on the architecture that is described in later in the text;
- Emphasis has been given to the ergonomics of the application, both on smartphone and on PC.

The following screenshots illustrate benefits from the visual representation of auscultation sounds in Pneumology and Cardiology.

The following pictures (figures 4 and 5) illustrate the results of automatic breathing cycles identification. The figure 4 illustrates detection of breathing in and breathing out signals, together with noise.

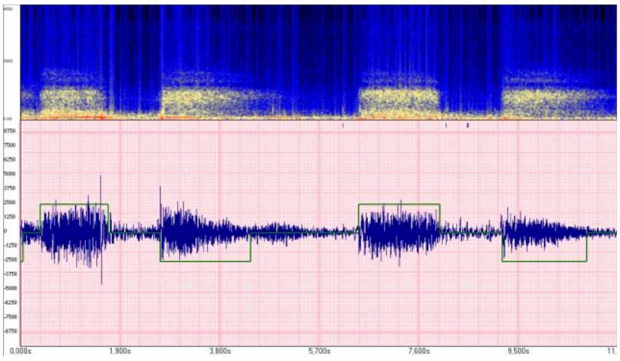

FIGURE 4: BREATHING CYCLES AND CRACKLES AUTOMATIC IDENTIFICATION (SPECIMEN OF SOUND FROM THE ASAP PROJECT).

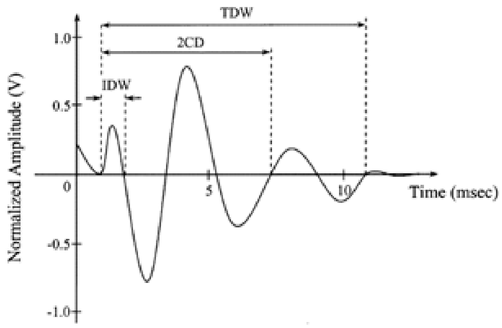

FIGURE 5: NORMALIZED CRACKLE WAVEFORM.

The figure 5 isolates the breathing in phases. This algorithm is based on *Alcatel-Lucent* VOIP technology, in particular voice activity detection algorithms. This will be used for accurate detection of crackles (to eliminate artefacts), and to help diagnosis by locating the crackles in the breathing cycle.

The figure 6 shows a breathing signal where the time representation is quite difficult to read. But the energy distribution in frequency representation shows dark red horizontal lines near 800 Hz: this is the "visual" marker of wheezes. This is the case of a child with bronchiolitis.

Automatic detection of wheezes in breathing sounds has been developed based on the characteristics of this signal following frequency domain analysis: the horizontal black lines show detected wheezes.

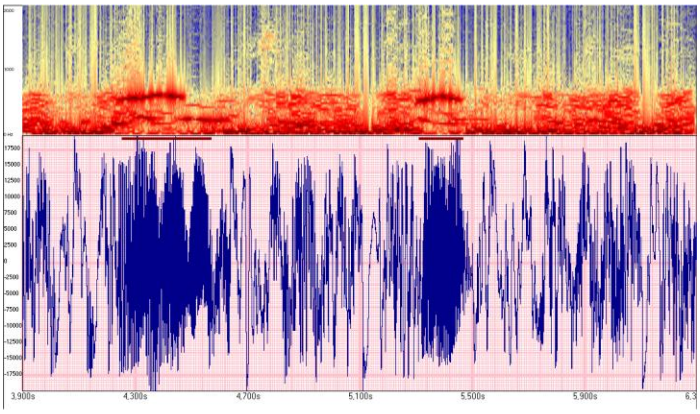

FIGURE 6: WHEEZE DETECTION IN BRONCHIOLITIS RECORD (SPECIMEN OF SOUND FROM THE ASAP PROJECT).

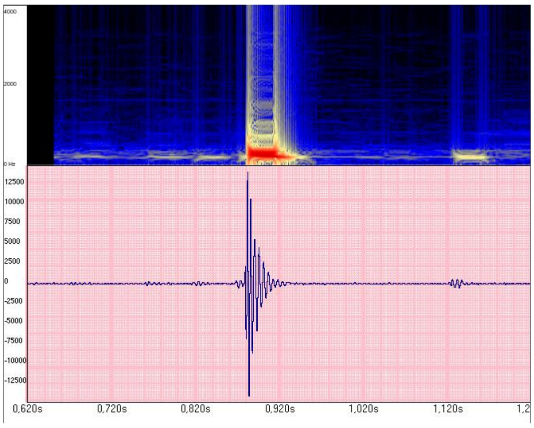

FIGURE 7: ACOUSTIC SIGNATURE OF A CARBON ARTIFICIAL VALVE (SPECIMEN OF SOUND FROM THE ASAP PROJECT).

The next signal was captured on a patient equipped with artificial valves that show their signature together with the S1 and S2 pulses in the figure 7. Application of the electronic stethoscope together with signal processing tool analyses the acoustic signature of the artificial valve and checks for drifts from the nominal.

The figure 8 shows the contribution of our electronic stethoscope in the framework of an infringement of the aortic valve. This later was not audible to the ear (even by many cardiologists experts), but documented with our prototype of digital stethoscope (figure 8a) and echocardiography (figure 8b).

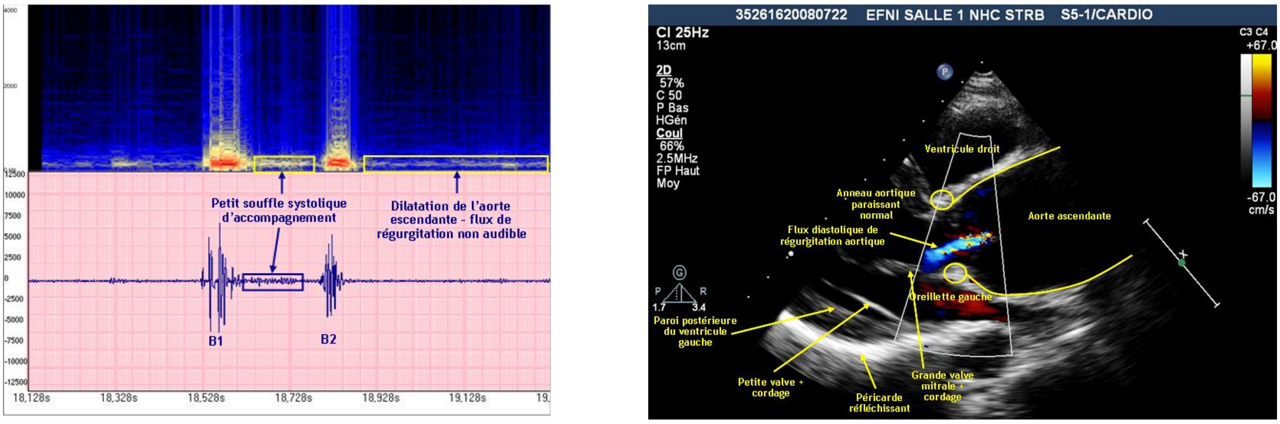

FIGURE 8: FEED NOT AUDIBLE REGURGITATING AORTIC VALVE(SPECIMEN OF SOUND FROM THE ASAP PROJECT).

V. A TELEMEDICINE SOLUTION: *BLUEHEALTH* PROJECT

Considering that some vendor of health related parameters measurement devices are beginning to brand products able to transmit physiological data over *Bluetooth*, based on the specifications that have been released by the *Bluetooth* Special Interest Group, the proposal is to collect, analyse et transmit signals when this is needed, so as to build an end to end solution for healthcare.

Our *Bluetooth* stethoscope (*eStetho*) is a potential candidate component as part of a global telemedicine solution. The described solution allows for [9]:

- Collection, cleaning and record of physiological data in streaming mode; with primary focus on auscultation sounds for lung and heart analysis;
- Formatting xml based metadata to carry administrative information related to the patient, to the practitioner, to the device, to the institution, etc., together with physiological data that are non-streaming with a first set of parameters that are solely numbers (weight, blood pressure, glucose-meter, fluid balance, thermometer, fall detector, bed sensor), and a second set of parameters that are files (DICOM images, jpeg images, etc.) or that are streaming data (pulse oxymeter, EKG/ECG, EEG, spirometer, auscultation);
- Transmission of data (protection, confidentiality, access rights, sharing, etc.);
- Processing (signal processing) of the data for diagnostic help;
- Multimedia communication, with audio over IP and display of the record on IPTouch or any other xml compatible device.

VI. USE CASES OF OUR DIGITAL STETHOSCOPE

One of the greatest challenges that will face health care professionals to the beginning of the twenty-first century will be the increasing burden of chronic diseases. More than 15 million patients today contract such diseases and the expected figure amounts to 20 million by 2020 [10].

These chronic diseases or disorders are defined by the *World Health Organization* (*WHO*) as requiring "on-going management over a period of years or decades" and cover a wide range of health problems. In industrialised countries, the four main expected chronic diseases are: heart failure (HF), chronic obstructive pulmonary disease (COPD), cognitive disorders (as Alzheimer disease) and cancers [10]. Other disorders may also be observed in the future as diabetes mellitus, obesity, hypertension, renal failure and anaemia. About 80% of older adults have at least one chronic disease, and 68% have at least two.

In response to the emerging challenge posed by chronic diseases, telemedicine may offer a promising solution. This is particularly the case in chronic diseases in which early detection of impairment and/or complication may be detected.

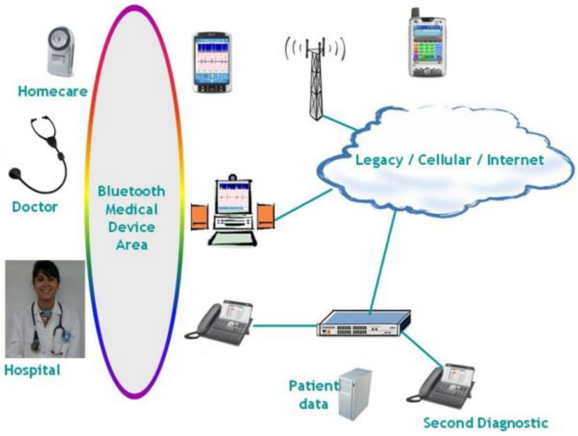

FIGURE 9: *ESTETHO* OVERALL ARCHITECTURE.

The figure 9 shows the general architecture we proposed for home and on the move patient auscultation, primary and emergency care, education, second diagnostic networks and hospital infrastructure.

6.1 Homecare and emergency care

This use case includes *eStetho*, local computing, cellular or internet terminals, GP and / or call centres (figure 10).

The patient collects health data through the use of one or more sensors, including the digital stethoscope. *Bluetooth* technology is used to connect these sensors to a first level of computation (smart phone, PC) to process data and participate to patient education.

Data are collected and processed locally to allow for summary reports to be given to the patient or to be sent to the care provider (call center) or Doctor. An innovative xml scheme has been defined to carry documented records between terminals and patient databases. In addition, a critical situation may generate an automatic alarm. Alternatively, real time streaming may be established for remote auscultation. This will require secured transmission with possibly the additional use of a webcam.

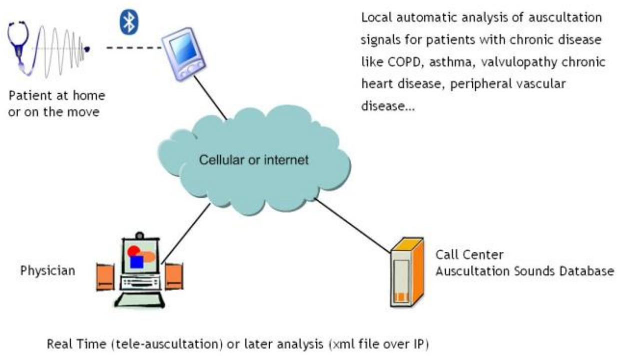

FIGURE 10: USE CASE: HOMECARE AND EMERGENCY CARE (ESPECIALLY FOR PATIENTS WITH CHRONIC DISEASES).

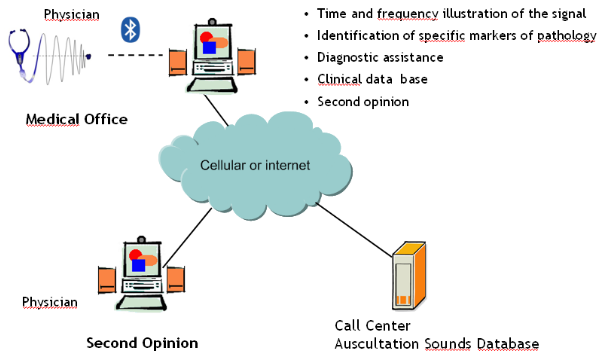

FIGURE 11: USE CASE: GENERAL PRACTITIONER.

6.2 General practitioner

The use case for general practitioner is represented in the figure 11.

General practitioner will benefit:

- From time and frequency domain representation to aid in diagnostics establishment;
- Obtaining a second opinion;
- Providing a database of signals for teaching;

- Have an objective track of patient's evolution, educating medical professionals.

6.3 Hospital

In the use case of hospital, information related to a specific patient may come from many different sources. Again thanks to standards, this is often successfully brought together towards a Doctor's PC to provide a patient-specific context for the efficient support of clinical decisions.

The next step is to allow the patient context to follow a medical professional so that appropriate information is available from any device, anywhere, using an intuitive man-machine interface, and with secure access to data.

The figure 12 illustrates *Bluetooth* connectivity over LAN infrastructure offered by IP phones. A GUI (Graphical User Interface) has been developed in the IP phone to offer access to patient data such as a previous auscultation, an ECG, etc., but also to have a first visual representation of auscultation sounds, and access to the patient database.

Such phones are made available in the rooms of the patient, to be uses as ordinary telephone set, but also as an entry point for the medical data.

The *Bluetooth* connectivity between the cordless handset and the phone is being used to transport the signal generated by auscultation or EKG or spirometer or EEG to a remote location for remote aided diagnostic or training or to a secured database.

One of the key benefits is the capability to perform the auscultation/EKG once, and to distribute it to as many recipients as necessary, those recipients being in the premises or anywhere else in the world. This can be done without any addition burden/constraint on the patient side.

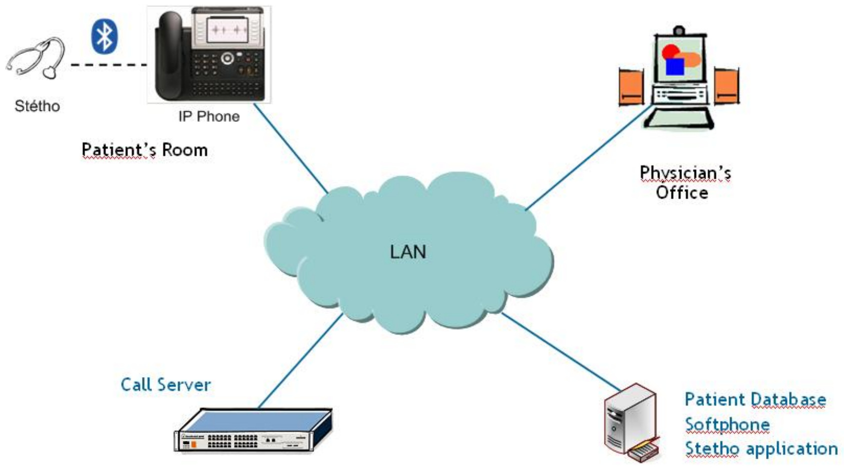

FIGURE 12: USE CASE: HOSPITAL. HOSPITAL ARCHITECTURE FOR DEDICATED HEALTH RELATED VLAN AND SERVERS.

6.4 Teaching

Unicast or multicast scenarios are used for real time second opinions but also for the training of medical students where an experienced Doctor also examines a patient. The stethoscope is commonly used for the evaluation of the heart or lungs condition of the patient.

The problem arising in this situation is that the stethoscope provides information only to the individual using it. During the examination the patient will be submitted into an unpleasant situation, with a number of students using the stethoscope in turns.

The proposed application (figure 13) provides means for collecting, storing and broadcasting auscultation patterns from one stethoscope to several headphones, together with visual representation of the lung or heart patterns.

The proposed configuration consists of the following elements:

- The *Bluetooth* stethoscope, connected to a dedicated IP phone;

- A VOIP connection through the PABX to a server for the storage and analysis of the auscultation sounds;
- Multicast of the auscultation sounds to a variable number of devices (fixed devices, that with the capability to see the sound, *Wi-Fi* equipped smart phones, Bluetooth headsets).

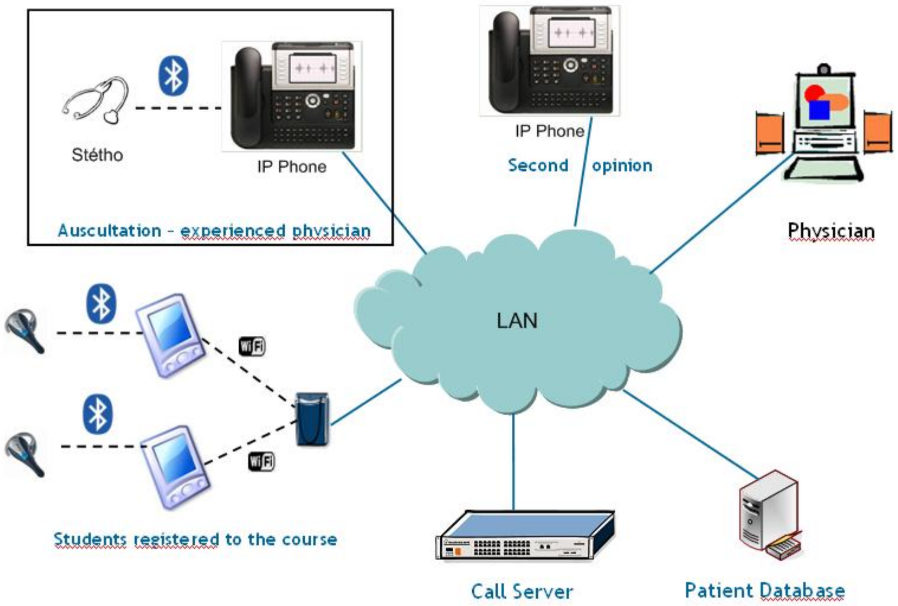

FIGURE 13: USE CASE: TEACHING. AUSCULTATION TEACHING IN PATIENT'S ROOM.

The availability of new technologies opens up interesting perspectives in the field of diagnostic tools, and also in education. The precise definition of these physical characteristics and the availability of new visual representations of sounds constitute exciting perspectives for teaching and pedagogy. The new intelligent communicating stethoscope systems could possibly contribute to a new auscultatory semiology, based on reliable methods of signal analysis and on visual display, and will be complementary to the acoustic signals perceived by the practitioner.

A study, conducted by our group, with a population of medical not graduate students allowed us to quantify better diagnostic "performance" with new auscultatory signal visualization tools in a setting of heart and lung disease assessment [11].

We asked a cohort of medical graduate students (n = 30) to listen to 10 sounds in order to diagnose heart and lung pathology. Not graduate students (second cycle of the medical studies) in first heard 10 sounds, they were then asked to check the appropriate box corresponding to the diagnosis relative to the sound they had just heard, as with an acoustic stethoscope (Day 0). The same exercise was conducted by adding the visual representation of the sound with pneumo-phonogram or phonocardiogram and spectrograms (Day 28).

At Day 0, the correct response rate was 40 to 51%. In the second instance at Day28, the rate of correct diagnosis reached 70 to 89%.

Thus in our experience, addition of visual representation of sounds has significant implications in terms of medical education, and also in term of decision-making, and potential patient safety.

VII. ARCHITECTURE OF THE SOLUTION *BLUEHEALTH*

7.1 Softphone architecture

The figure 14 describes the main modules of mPC (my Pocket Communicator) and the points were we have connected the stethoscope application.

Red boxes are from the host (PC or smart phone) library, yellow ones are user plane of the telephony application that need to be developed to support for IP channels, green boxes are those functions from smart phone that may be reused by stethoscope (AGC for better control of inputs and protection against acoustic chock, VAD algorithm that has been tuned to detect breathing cycles, echo cancelling that will be adapted for ambient noise cancellation).

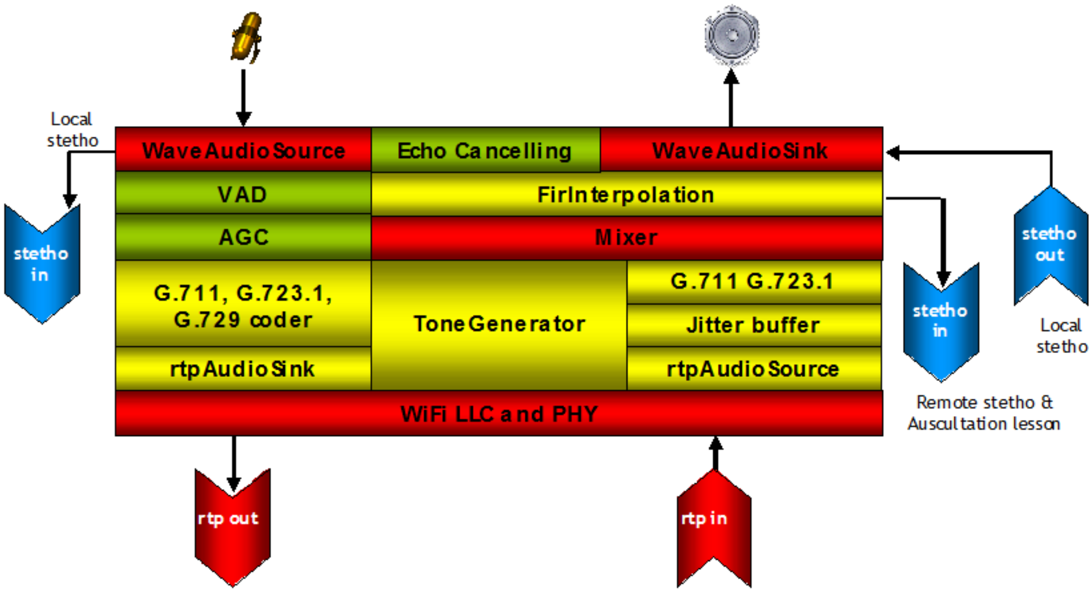

FIGURE 14: SOFTPHONE (MPC) ARCHITECTURE

7.2 eStetho architecture

Figure below describes the main modules of the stethoscope application.

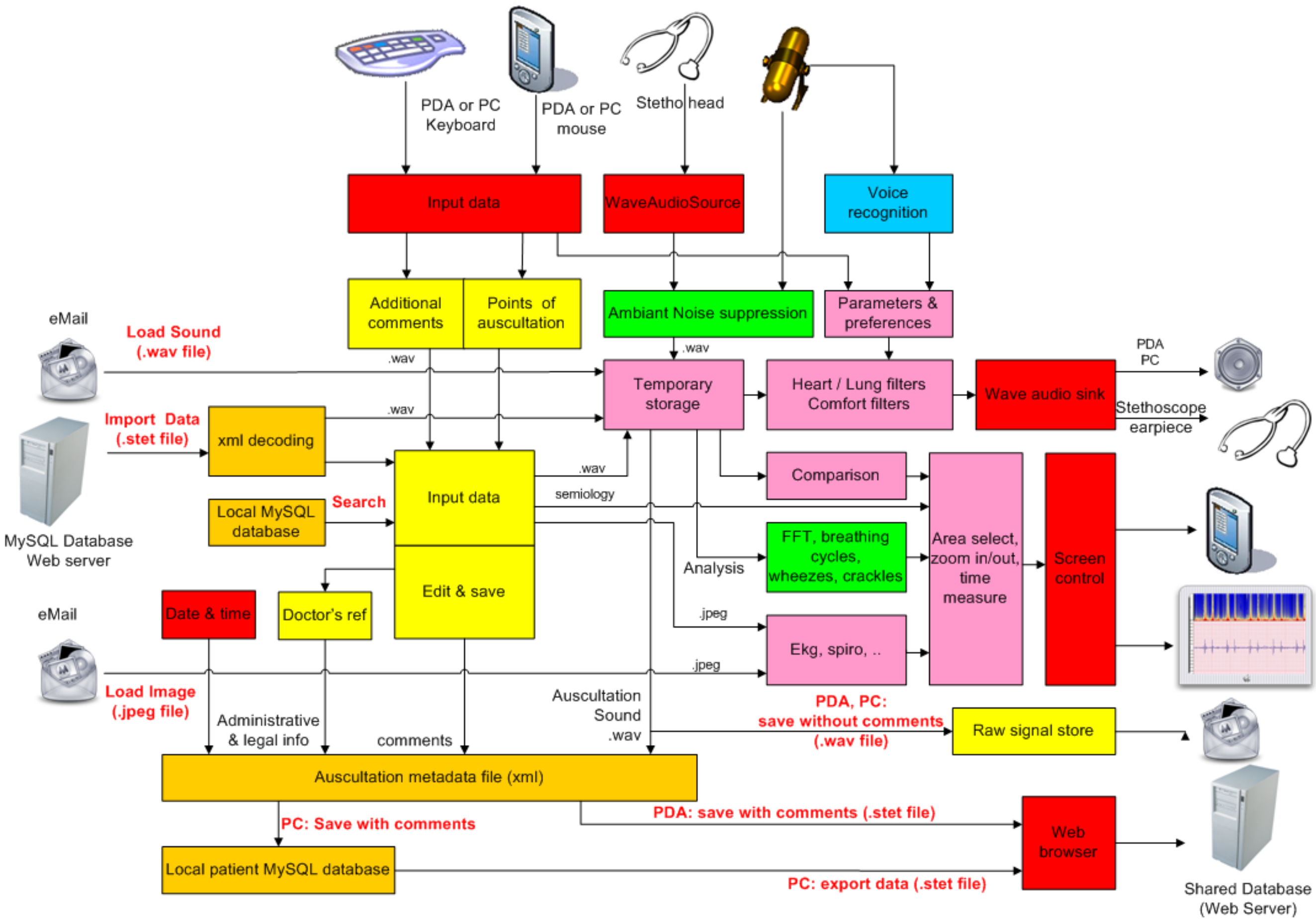

FIGURE 15: *eStetho* ARCHITECTURE.

Red boxes in the figure 15 are from the host (PC or smartphone) library, pink ones are new developments for stethoscope plane, green boxes are those functions from the smartphone that will be reused by stethoscope (AGC for better control of inputs and protection against acoustic chock, VAD algorithm that has been tuned to detect breathing cycles, echo cancelling that will be adapted for ambient noise cancellation), yellow and orange boxes are those functions of stethoscope, that are related to data formatting (xml based) and database handling (MySQL). The blue box (voice recognition) is used for voice control of the device, so as to overcome the limitations of the CKPD capabilities limitations on smartphones and PCs.

Red text corresponds to the semantics of the controls available with the stethoscope application.

To meet the constraints imposed by the medical world, several additional components were developed and included in our solution:

- Authentication;
- Encryption (guarantee confidentiality and prevent tapping);
- My Instant Communicator on IP Touch (telephony, IM, presence, collaboration..);
- My Instant Communicator on IP Touch for healthcare which would become a menu driven access to initiate the transport of information (XML), automatic or easy association between *Bluetooth* IP Touch phones and medical equipment.

In the hospital, the purpose of the server is:

- Collect data from various medical devices or operator;
- Provide signal processing (signal cleaning, occurrence finding);
- Store and retrieve signal records in a database;
- Display the records by usinggraphical forms on the digital phone;
- Manage security (access control, user authentication, availability…);
- Keep record transaction (may be required for HIPAA compliance purpose);

The Prototype currently available and is based on the following components:

- ".net server";
- Presentation server;
- Signal processing application;
- It gives the possibility to format and send any XML content on IP Touch phones;
- They can be used to view and hear in real time the results of auscultation/EKG anywhere in the campus, physician offices, nurse room, medical school, labs, surgeon offices…. ;
- Use of smart PRS, in order to provide the consultation/display service on a smartphone with MyIC mobile should be seen as a step 2.

Additional sensors will be included in the patient area network, to offer individual or multiple simultaneous, synchronous measurements and analysis, storage, and transmission (alarm, reporting, or real time streaming). Biological parameters will be transmitted over *Bluetooth* to the local processing unit (cellular phone, smartphone, PC) that will store, analyse, send alarms over cellular or IP networks, and send periodic or real time reports. The following sensors have been identified for inclusion in the second phase of the project and potential partners have already been contacted:cardiac telemetry for arrhythmia monitoring; oxymeter for the measurement of oxygen saturation; weight; blood pressure and pulse rate; glucose measurement; spirometer and body temperature.

VIII. CONCLUSION

We have developed and experienced a telemedicine solution, called *BlueHealth*. This described solution, including a digital stethoscope, allows for:

- Collection, cleaning and record of physiological data in streaming mode; with primary focus on auscultation sounds;

- Formatting xml based metadata to carry administrative information related to the patient, to the practitioner, to the device, to the institution, etc., together with physiological data that are non-streaming with a first set of medical parameters;
- Transmission of data (protection, confidentiality, access rights, sharing, etc.),
- Processing (signal processing) of the data for diagnostic help,
- Multimedia communication, with audio over IP and display of the record on IPTouch or any other XML compatible device.

Market targets are medical application of information sharing and consultation (Medical Staff meetings, training). Such approach remains relevant in Emergency situation where remote transmission from crisis area to emergency service may allow "pre care/ pre-processing" of the patient issue together with transmission of physiological parameters measurement between emergency team and hospital desk.

The following components need to be added to the existing prototype of our telemedicine solution to go to the market:

- Security (authentication, encryption, authorization…) for local and remote database access;
- Certification (US [FDA], Europe [EMEA], France [ANSM]);
- PRS robustness: Windows last version of the PRS goes down following quick multiple presses on a key; we have developed a dll that avoids PRS crash, but this makes a specific version of PRS. This bug should be corrected in the generic version of the PRS.

CONFLICT OF INTEREST: NONE.

Grants: STETAU project: grant from the Direction Générale de l'Entreprise, 2005) and ASAP project from the AgenceNationale de la Recherche, 2006) - French Government to promote translational research.

REFERENCES

[1] Andrès E. Stethoscope: a still relevant tool and medical companion. Am J Med 2016; 129: e37-e38.

[2] Andrès E, Gass R, Brandt C, Reichert S, Collet C, Nguyen G, Baldassari C. De nouveaux outils au service de l'auscultation. IRBM 2008; 29: 337-9.

[3] Reichert S, Gass R, Brandt C, Andrès E. L'auscultation pulmonaire à l'ère de la médecine factuelle. Rev Mal Respir 2008; 25: 674-82.

[4] Andrès E, Reichert S, Gass R, Brandt C. A French national research project to the creation of an auscultation's school: the ASAP project. Eur J Intern Med 2009; 20: 323-7.

[5] Andrès E, Gass R, Brandt C. Etat de l'art sur les stéthoscopes électroniques en 2015. Médecine Thérapeutique 2015; 21: 319-32.

[6] http://www.telemedecine-alsace.fr/multi/stetau/stethos_stetau.html, April 2016.

[7] http://miv.u-strasbg.fr/collet/ftp/Projets/ASAP.pdf, April 2016.

[8] Reichert S, Gass R, Brandt C, Andrès E. Analysis of respiratory sounds: state of the art. Clinical Medicine Circulatory Respiratory Pulmonary Medicine 2008; 2: 45-58.

[9] http://www.telemedecine-alsace.fr/publications/publications.htm, April 2016.

[10] http://www.who.int/chp/chronic_disease_report/full_report.pdf, April 2016.

[11] Andrès E, Brandt C, Mecili M, Meyer N. Intérêt d'une démarche pédagogique structurée associée à de nouveaux outils de visualisation des signaux auscultatoires dans le cadre de l'apprentissage de la sémiologie auscultatoire: étude prospective auprès de 30 étudiants du deuxième cycle des études médicales. Pédagogie Médicale 2012; 13: 39–50.