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ORIGINAL ARTICLE / *Remote Medical Assistance*

Development and experimentation of a new digital communicating and intelligent stethoscope

Développement et expérimentation d'un nouveau stéthoscope numérique, communiquant et intelligent

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Summary
Introduction. — We have previously developed a communicating and intelligent electronic digital stethoscope. Part of the developments has been conducted in collaborative and institutional projects. These research projects resulted in the implementation of a Bluetooth electronic stethoscope (eStetho), together with signal processing and data communication techniques.
Materials and methods. — The main objective of the present work was the validation of the technological and medical choices by healthcare professionals, in a university hospital setting.

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For that, eStetho has been compared with acoustic stethoscopes in two prospective studies: the PRI stéthoscope study, including more than 160 patients, and an education study, including 30 students.
Results. — In this analysis, the eStetho system allowed us to have a correct diagnosis in 10% more cases than with an acoustic stethoscope. An improvement of good diagnoses (recognition of heart and respiratory sounds) between 20 to 30% is also observed with 30 students of the second cycle of their medical studies.
Discussion. — Whilst conventional stethoscope auscultation is subjective, hardly sharable and interpreted by a single clinician, the characterization and identification of sounds by computer-based recording and analysis systems provide objective and early diagnostic help along with better sensitivity and reproducibility when interpreting findings.
Conclusions. — The eStetho system allows for the optimization of auscultatory findings, hence achieving a correct diagnosis by physically characterizing sounds through recordings, visualization and automated analysis systems.

MOTS CLÉS
Stéthoscope ;
Auscultation ;
Hôpital ;
Enseignement ;
Bluetooth

Résumé
Introduction. — Nous avons précédemment mis au point un stéthoscope électronique numérique communicant et intelligent. Une partie des développements a été menée dans des projets collaboratifs et institutionnels. Ces projets de recherche ont abouti à la mise au point d'un stéthoscope électronique Bluetooth (eStetho), associé à des techniques de traitement du signal et de la communication de données.
Matériels et méthodes. — L'objectif principal du présent travail est la validation des choix technologiques et médicaux par des professionnels de la santé dans le cadre d'un centre hospitalo-universitaire. Pour cela, le system eStetho a été comparé à des stéthoscopes acoustiques dans deux études prospectives : l'étude PRI stéthoscope, incluant plus de 160 patients et une étude pour tester l'apport éducationnel, incluant 30 étudiants.
Résultats. — Dans cette analyse, le système eStetho nous a permis d'avoir un diagnostic correct dans 10 % des cas de plus qu'avec les stéthoscopes acoustiques. Une amélioration entre 20 à 30 % de ces bons diagnostics (identification des sons cardiaques et pulmonaires) a également été observée chez 30 étudiants du deuxième cycle des études médicales.
Discussion. — Alors que l'auscultation à l'aide d'un stéthoscope conventionnel est subjective, non partageable, et interprétée par un seul clinicien, la caractérisation et l'identification des sons, leur enregistrement et l'analyse par des systèmes informatiques fournissent une aide diagnostique objective et précoce ainsi qu'une meilleure sensibilité et reproductibilité lors de l'interprétation des résultats.
Conclusions. — Le système eStetho permet une optimisation de l'auscultation et la réalisation d'un diagnostic correct en caractérisant physiquement les sons à travers des enregistrements, la visualisation et des systèmes d'analyse automatisée.

Introduction

Auscultation of a patient's heart or lungs is part of the doctor's professional services [1]. Invented in 1816 by René Laennec, the first versions of the single ear stethoscope replaced the practice of mediate auscultation (the doctor directly applied his ears against the chest of the patient) [2]. 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, would make it easy to provide objective analysis of auscultation records and probably facilitate teaching auscultation [2].

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

Figure 1. Several prototypes of the digital stethoscope that we developed.
Différents prototypes du stéthoscope électronique que nous avons développés.

In this paper, we report an evaluation in medical settings of a new communicative and intelligent digital stethoscope called eStetho.

Material, subjects, method

Objective

The main objective was the validation of the technological and medical choices, related to a communicative and ''intelligent'' digital stethoscope (eStetho), by healthcare professionals. For that, successive prototypes of our stethoscope (Fig. 1) were deployed in medical settings and used to monitor patients and to facilitate interaction between healthcare professionals. In this phase, we tested various prototypes to improve the functionalities and the ergonomics, to detect any vulnerability, and to identify the strengths of our digital stethoscope. The prototypes were compared with conventional acoustic stethoscopes (mainly 3M™ Littmann® Classic III™ Stethoscope/3M United States).

The developments of our digital stethoscope have been partially conducted through an institutional project: the PRI stéthoscope (''perspectives et apports du développement d'un stéthoscope communicant à l'ère de la télémédecine'' [perspectives and contributions of the development of a communicating stethoscope in the era of telemedicine], grant from the University Hospital of Strasbourg, 2008).

In addition, we tested and studied our stethoscope with medical students and investigated the potential contribution of the system, particularly on the diagnostic value and for the education of the students.

Material

We have previously developed a communicative and intelligent electronic digital stethoscope [2,3]. Part of these developments has been conducted in collaborative projects between Alcatel-Lucent, the université de Strasbourg and the hôpitaux universitaires de Strasbourg (together in Strasbourg, France).

These developments have been partially conducted through two main institutional projects: the STETAU (''stéthoscope'', grant from the direction générale de l'entreprise [the French directorate general for enterprise], 2005) and the ASAP (''analyse des sons auscultatoires pathologiques'' [analysis of pathological auscultatory sounds], grant from the French national agency for research, 2006); projects designed in the framework of the national program from the French Government to promote translational research [3,4].

These research projects resulted in the implementation of a Bluetooth electronic stethoscope (eStetho), together with signal processing and data communication techniques (Fig. 1) [3,4]. The second step of our research has consisted of the connection of additional Bluetooth-enabled sensors to allow for multiple synchronous analyses, such as heart auscultation together with electrocardiogram (ECG) to eliminate artifacts and improve the accuracy of the diagnosis.

The main characteristics of our prototypes of digital stethoscope are [3,5]:

- an electronic stethoscope offering Bluetooth connectivity that covers the [10—4,000 Hz] frequency range (Fig. 2);
- various stethoscope mechanics have been tried to provide the ergonomics that are familiar to medical experts;

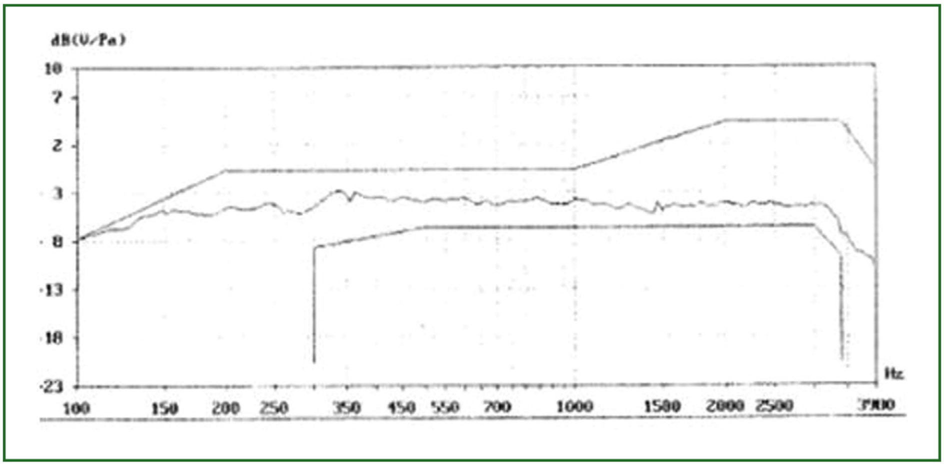

Figure 2. Response curve of the digital electronic stethoscope, which was developed by Alcatel-Lucent.
Courbe de réponse du stéthoscope digital qui a été développé par Alcatel-Lucent.

- 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, e.g. for communication between healthcare professionals;
- emphasis has been given to the ergonomics of the application, both on smartphone and on PC.

Several softwares were developed and added to the eStetho system, allowing an automatic analysis of the heart and lung signal (''intelligent'' stethoscope) (Medetel conference, 2007) [3].

The prototypes of our digital stethoscope (eStetho) have been experimented at the hôpitaux universitaires de Strasbourg (in Strasbourg, France), a university hospital referral center. The prototypes were deployed and used to monitor patients and to facilitate interaction between healthcare professionals. Bluetooth connectivity inside the hospital, together with mobile voice-over Wi-Fi technology, should 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.

In the use case of hospital, information related to a specific patient may come from many different sources. 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.

Fig. 3 illustrates Bluetooth connectivity over LAN infrastructure offered by IP phones. A graphical user interface

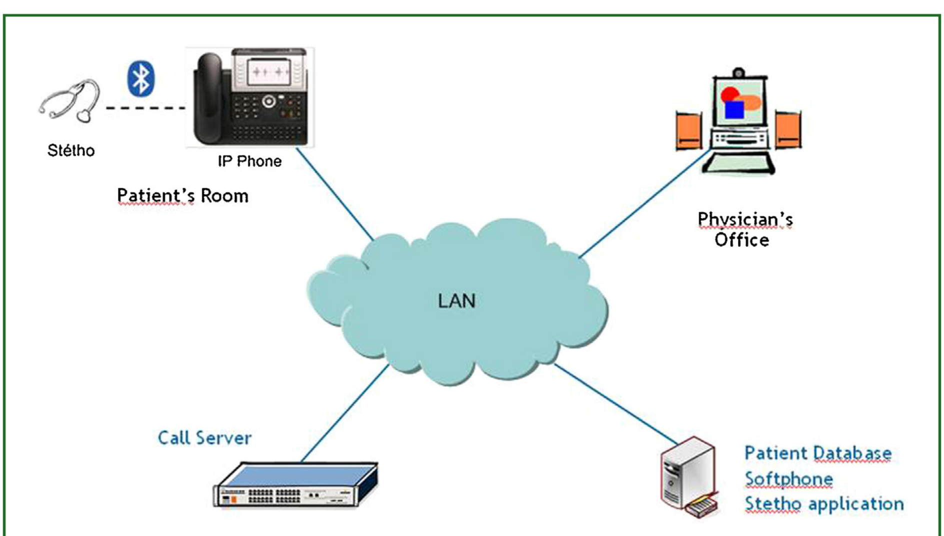

Figure 3. Use case in hospital environment. Hospital architecture for dedicated health related VLAN and servers.
Utilisation en milieu hospitalier. Architecture hospitalière dédiée à la santé, composants du système et serveurs.

(GUI) 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 theoretically available in the rooms of the patient, to be used as an ordinary telephone set, but also as an entry point for the medical data.

The Bluetooth connectivity between the cordless handset and the phone is used to transport the signal generated by auscultation or ECG or spirometer or electroencephalogram (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 on the premises or anywhere else in the world. This can be done without any additional burden/constraint on the patient's side.

The system with the prototypes of the digital stethoscope (eStetho) has been deployed in 2006 in a 20-bed unit of the department of internal medicine, diabetes and metabolic diseases of the hôpitaux universitaires de Strasbourg (in Strasbourg, France). This unit is ''open'' to the emergency wards. All consecutive adult patients of the 20-bed unit were considered to be included in the study. Around 800 patients are hospitalized in this unit per year. The patient profile included in this experiment was: elderly patient (mean age: 82 years); with several chronic diseases such as: chronic heart failure (> 60%), anemia (> 40%), type 2 diabetes (> 30%), chronic obstructive pulmonary disease (COPD) (> 30%). In 25% of cases, patients present a total loss of autonomy. The number of healthcare professionals includes: experienced doctors (senior) (n = 2), doctors in training (junior) (n = 2), nurses (n = 8), and medical students (n = 6).

In this experimental phase, we empirically validated the technological and medical choices related to the eStetho system in clinical practice (in real word and life). Over 2000 auscultations were performed by the healthcare professionals of the department.

The digital stethoscope operated perfectly and the experimental phase enabled us to validate the technological choices. A qualitative survey of the healthcare professionals helped to positively assess the system's ergonomics. The analysis in real time of the various diagnoses from the various realized auscultations (murmurs, crackles, wheezes and arterial pressure) revealed a concordance between the acoustic devices used on a daily basis in the hospital and those proposed by eStetho.

This experimental phase allowed us to show that the system offers for doctors the following:

- time and frequency domain representation to aid in diagnostics establishment;
- obtaining a second opinion;
- providing a database of signals for teaching;
- having an objective track record of patient's evolution, educating medical professionals.

In the Appendix A, Figs. A1 et A2 illustrate the results of automatic breathing cycle's identification.

We also spent a large part of our developments to promote research on auscultation and education through this new tool. We collected the lung and heart sounds. These sounds will be used for new research programs, with the main goal of identifying specific markers that are not yet known because they were not accessible to human ears or with electronic stethoscopes currently available on the market. Our university also showed interest in setting up new material for teaching auscultation (faculté de médecine de Strasbourg [in Strasbourg, France]).

The proposed system 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 (Fig. 4).

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, those with the capability to see the sound, Wi-Fi equipped smartphones, Bluetooth headsets).

Method and subjects

PRI Stéthoscope study

The PRI stéthoscope project (''perspectives et apports du développement d'un stéthoscope communicant à l'ère de la télémédecine'' [perspectives and contributions of the development of a communicating stethoscope in the era of telemedicine], grant from the University Hospital of Strasbourg, 2008) is an institutional project dedicated to the validation of our digital stethoscope in hospital. In this project, eStetho is compared to acoustic stethoscopes in a prospective study.

In this study, the principal criterion is the diagnostic capacity of eStetho with those proposed by the acoustic auscultation (3M™ Littmann® Classic III™ Stethoscope/3M United States), by comparison with the final diagnosis. This later is based on the advice of doctors in charge of the patient, analysis of medical file, and results of echocardiography and lung CT scan.

This study is taking place in the department of internal medicine, diabetes and metabolic diseases and in the departments of cardiology of the hôpitaux universitaires de Strasbourg (in Strasbourg, France).

Education project

To test the eStetho system in a view of education and teaching, we asked a cohort of medical graduate students (n = 30) to listen to 10 sounds (wheeze, crackles, systolic ejection murmur from an aortic regurgitation...) in order to diagnose heart and lung pathology.

Students of the second cycle of the medical studies 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) (Fig. 5).

All questionnaires were analyzed. Each of those included, in addition to diagnosis related to heard sounds — ''good''

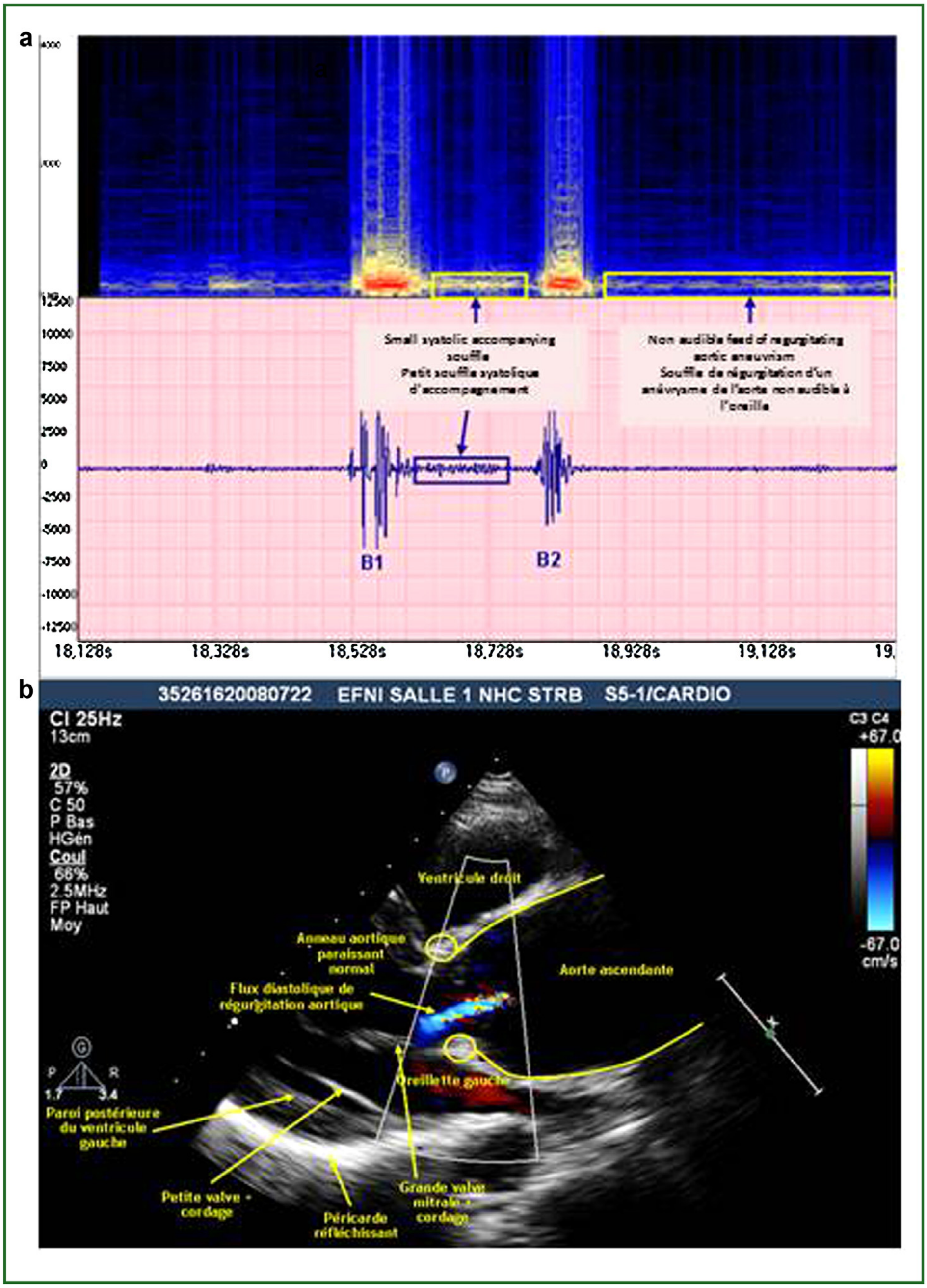

Figure 4. Use case for teaching. Auscultation teaching in patient's room.
Utilisation pour l'enseignement. Enseignement de l'auscultation au chevet du patient.

or ''bad'' with or without visual aids — the demographic characteristics of the student (age, gender), as well as their level (year) of study in the second cycle of medical studies).

The medical students included in this study were 5th- and 6th-year medical students of the faculté de médecine de Strasbourg during their full-time immersion internship at the university hospital of Strasbourg (together in Strasbourg, France).

Statistical analysis

The results are expressed in absolute value and percentage. Comparisons between groups were carried out by testing Chi^2 and Student and especially by the Cochran Q test allows compare two paired samples with values are binary. A *P* value less than 0.05 was considered significant statistically.

Administrative authorizations

A file was submitted to the commission nationale des libertés (CNIL), a national commission on computer security.

The study was presented to the local ethics committee who gave permission for the eStetho system experimentation.

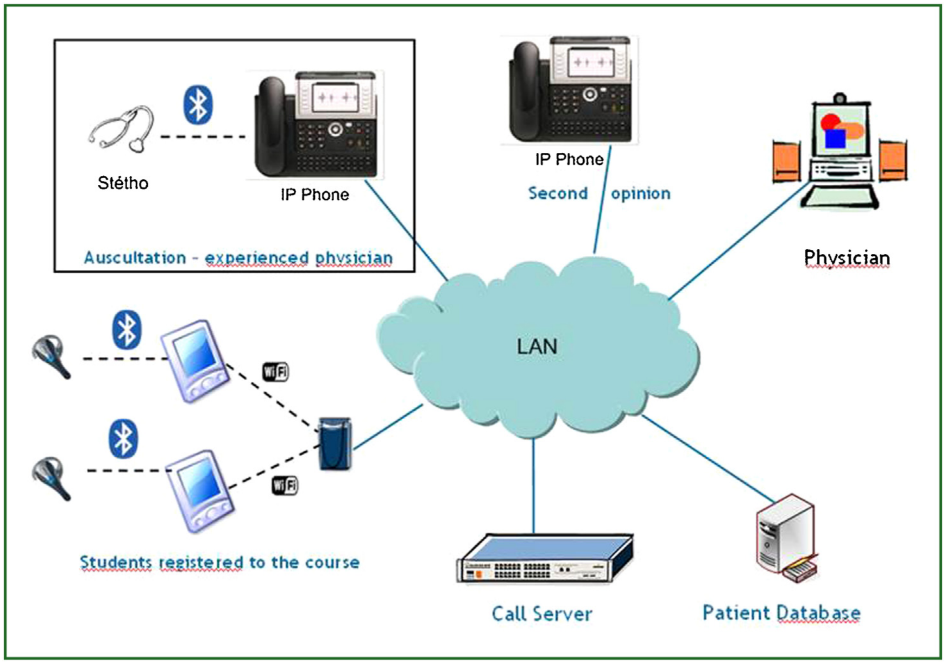

Figure 5. Representation of a cardiac auscultation related to an aortic stenosis with a systolic ejection murmur (indicated by a white arrow) in the form of a phonocardiogram (2a) and a spectrogram (2b).
Représentation d'une auscultation cardiaque en rapport avec une sténose aortique avec un souffle éjectionnel (indiqué par des flèches blanches) sur le cardiophonogramme (2a) et sur un spectrogramme (2b).

Results

Results of the PRI Stéthoscope study

One hundred sixty patients have been included in the PRI stéthoscope study. The patient profile included in this experiment was: younger subjects (mean age: 45 years); healthy subjects in regards of lung and heart disorders ($n = 55$), various heart disorders (ischemic heart disorders, valvular heart disorders, acute heart failure...) ($n = 80$), and lung disorders (COPD, pneumonia, asthma) ($n = 27$).

An analysis of the diagnoses revealed a very good concordance between the medical file, including acoustic auscultation, echocardiography and lung CT scan and those proposed by eStetho system, with a K value of 0.89. In this analysis, the eStetho system allowed us to have a correct diagnosis in 10% more than an acoustic stethoscope.

For example, Fig. 6 shows the contribution of our electronic stethoscope in the framework of an infringement of the aortic valve. The latter was not audible to the ear (even by many expert cardiologists), but documented with our prototype of digital stethoscope (Fig. 6a) and echocardiography (Fig. 6b).

Results of a teaching experimentation

The results of this experimentation allowed us to quantify better diagnostic ''performance'' with the new auscultatory signal visualization tools form eStetho, in a setting of heart and lung disease assessment (Table 1).

At day 0, 45% of correct diagnoses (identification of respiratory or heart sounds as wheeze, crackles, systolic ejection murmur from an aortic regurgitation...) and were observed for all students. For respiratory and heart sounds, we observed respectively 51 and 40% accurate diagnoses. On day 28, 80% of good diagnoses were reported for all students ($P < 0.01$ compared to day 0), with 70% of correct diagnoses for respiratory sounds ($P = 0.058$) and 89% for heart sounds ($P < 0.009$).

Discussion

As we have demonstrated, eStetho is a new communicating and intelligent digital stethoscope, quite suitable for healthcare professionals and medical students.

In the present studies, we have demonstrated the usefulness of the system in hospital and for teaching. In this experimentation, we assessed 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, to our opinion, makes it applicable to markets aimed at doctors.

Acquisition and analysis of human sounds are the basis of heart and lung medical examination [1,6]. Auscultation opened the door and helped to develop clinical disciplines by identifying heart and lung semiology [6]. Studies on the establishment of diagnostics 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.

The stethoscope evolved slowly during the 19th and 20th centuries to become in most cases a binaural tool [7]. They are usually made of a Y-shaped rubber tubing that acts as a

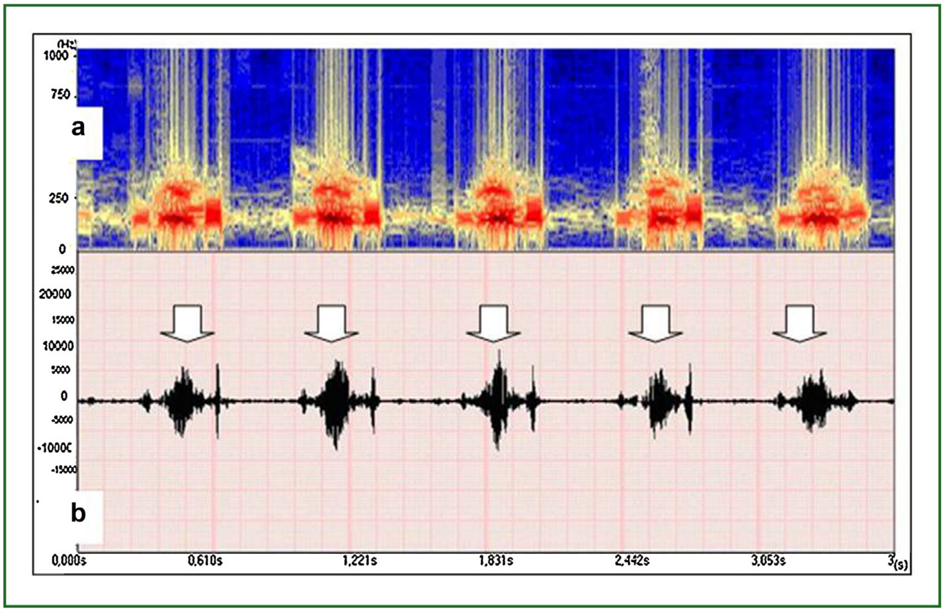

Figure 6. Non-audible feed [a] of regurgitating aortic aneuvrism (seen on echocardiography [b]).
Souffle de régurgitation d'un anévrysme de l'aorte non audible à l'oreille (a) (visualisé par l'échographie [b]).

wave guide to allows sounds to enter the device at one end, travel up the tubes and through to the ear pieces.

More recently, electronic stethoscopes have come onto the market that make use of a microphone located on a headset plus an amplifier and filters to mimic the two-sided head of a traditional stethoscope [2,7]. The major drawback with these first generation 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 (Fig. 7).

It is therefore essential for clinical use (''plus value'' [added value]) to:

- discriminate between noise and useful information;
- provide sound amplification that fulfills 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;
- cancel ambient noise.

In the hands of healthcare professionals (in hospital), the eStetho system allowed a correct diagnosis in 10% more than with an acoustic stethoscope. Same results (addition of 10% of good diagnosis with electronic stethoscope) are previously reported by Myint et Dilland. [8]. To date, with the eStetho (deployed in our department) or the second generation of electronic stethoscopes as the Model 32003M™ from Littmann® electronic stethoscope, we observed an improvement of the diagnosis (between 15—20%) related to their use in clinical practice (> 4000 auscultations), for nurses, students and experienced doctors (personal not published data).

Table 1 Results of the use of phono- and spectrogram for visualizing sounds in 30 medical students.
Résultats de l'utilisation des phono- et spectrogrammes pour la visualisation des sons chez 30 étudiants en médecine.

	Day 0	Day 28 without	Day 28 with tools	Comparison between day 0 and day 28 with tools
''Good'' diagnosis: identification of respiratory or heart sounds (as wheeze, crackles, systolic ejection murmur from an aortic regurgitation...)	45% (136)	64% (191)	80% (239)	$P < 0.01$
''Good'' diagnosis in respiratory auscultation: identification of respiratory sounds (as wheeze, crackles, ...)	51% (76)	61% (92)	70% (105)	$P = 0.058$
''Good'' diagnosis in cardiac auscultation: identification of heart sounds (as systolic ejection murmur from an aortic regurgitation...)	40% (60)	66% (99)	89% (134)	$P < 0.009$

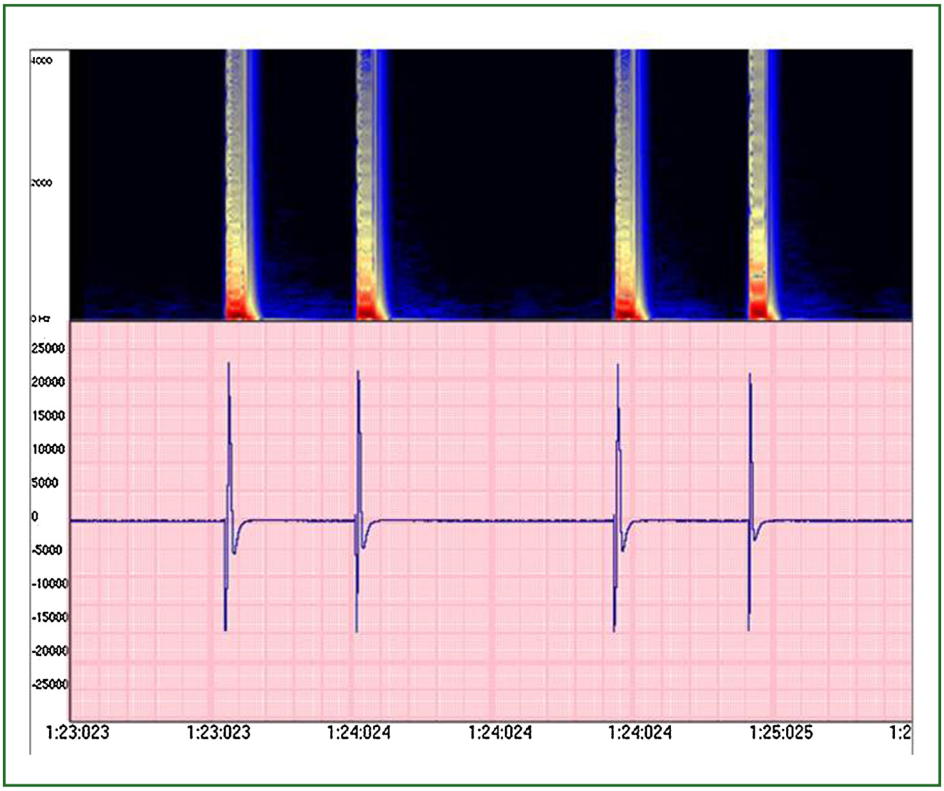

Figure 7. Current electronic stethoscopes of the market: Nice pictures, but a dangerous tool. With little clinical interest.
Stéthoscopes électroniques actuels: belle image, mais outils dangereux et sans intérêt sur le plan clinique.

The availability of these new technologies opens up interesting perspectives in the field of diagnostic tools, but also in education [8,9].

Whilst conventional stethoscope auscultation is subjective, hardly sharable, and interpreted by a single clinician, the characterization and identification of sounds by computer-based recording and analysis systems provide objective and early diagnostic help along with better sensitivity and reproducibility when interpreting findings [7,9].

The precise definition of the physical characteristics and the availability of new visual representations of sounds constitute exciting perspectives for teaching and pedagogy [9]. The new intelligent communicating stethoscope systems will 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 [9—11]. In fact, as well as providing a reliable addition to routine clinical diagnosis, these ''tools'' should ultimately lead to improvements in auscultatory training, based on the ''physical'' characterization of signals and sounds, as well as a visual representation in the form of phono- and spectrogram.

As we have demonstrated, 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 [9]. In the present study, 80% of good diagnoses were reported for all students ($P < 0.01$ compared to day 0), with 70% of correct diagnoses for respiratory sounds ($P = 0.058$) and 89% for heart sounds ($P < 0.009$).

In the future, our new digital stethoscope also offers the possibility to create an auscultation sounds database to support medical research [12]. It is in this context that a project known as ASAP: ''Analyse de Sons Auscultatoires et Pathologiques'' (Analysis of pathological auscultatory sounds) was developed by the French national agency for research (ANR 2006 - TLOG 21 04) [4,12]. This project was supported by the development and the provision of a new intelligent communicating stethoscope system. The main objective of this project was to bring auscultation into the era of evidence-based medicine, based on the identification of sounds using innovations in technology, mathematics and computer science in order to ''rediscover'' the clinical significance of respiratory sounds [8,12,13].

As another perspective, we are also assessing the development of a global telemedicine solution (the BlueHealth project) in relation with this electronic stethoscope. This project is developing an intelligent communicative platform enabling the home monitoring of patients with chronic diseases (heart failure, COPD...) [14].

This described solution, including our 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.

Conclusions

Conventional auscultation is subjective and not easily shared. The eStetho system allows for the optimization of auscultatory findings, hence achieving a correct diagnosis by physically characterizing sounds through recordings, visualization and automated analysis systems. The development and availability of new communicating intelligent stethoscopes based on innovations in science and communications technology provide the clinician, but also the students with an invaluable aid in order to achieve an objective diagnosis, as well as offering increased sensitivity and reproducibility of auscultatory findings. Such advances have significantly contributed to the revival of auscultation, in telemedicine, particularly as a diagnostic and teaching aid, e-teaching and pedagogy.

Grants

ASAP: ''analyse des Sons auscultatoires pathologiques'', from the Agence nationale de la recherche, 2006; PRI stéthoscope: ''perspectives et apports du développement d'un stéthoscope communicant à l'ère de la télémédecine'', from the university hospital of Strasbourg, 2008.

Authors' contributions

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

Appendix 1.

Fig. A1 isolates the breathing in phases. This algorithm is based on Alcatel-Lucent VOIP technology, in particular voice activity detection algorithms. This is also used for accurate detection of crackles (to eliminate artifacts) and to help diagnosis by locating the crackles in the breathing cycle.

Fig. A2 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.

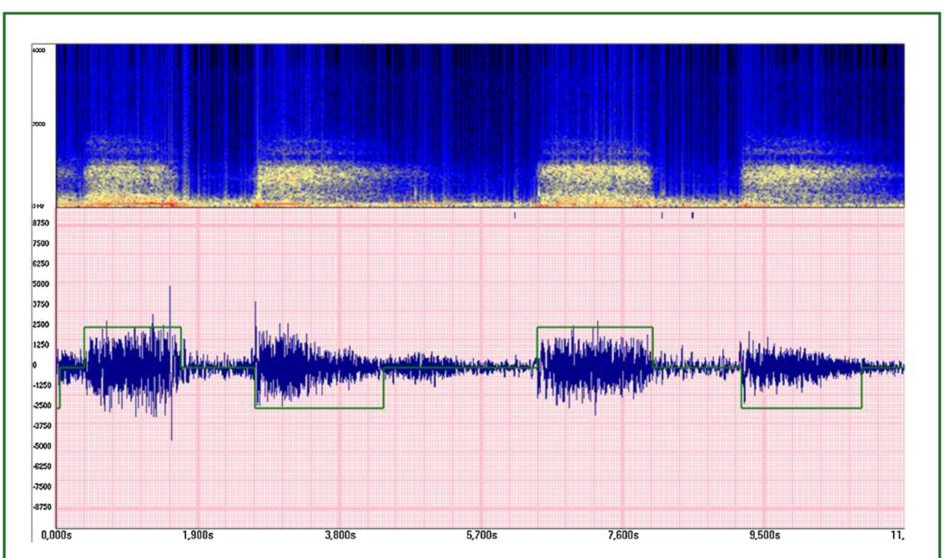

Figure A1. Breathing cycles and crackles' automatic identification.
Cycles respiratoires avec détection automatique des crépitants.

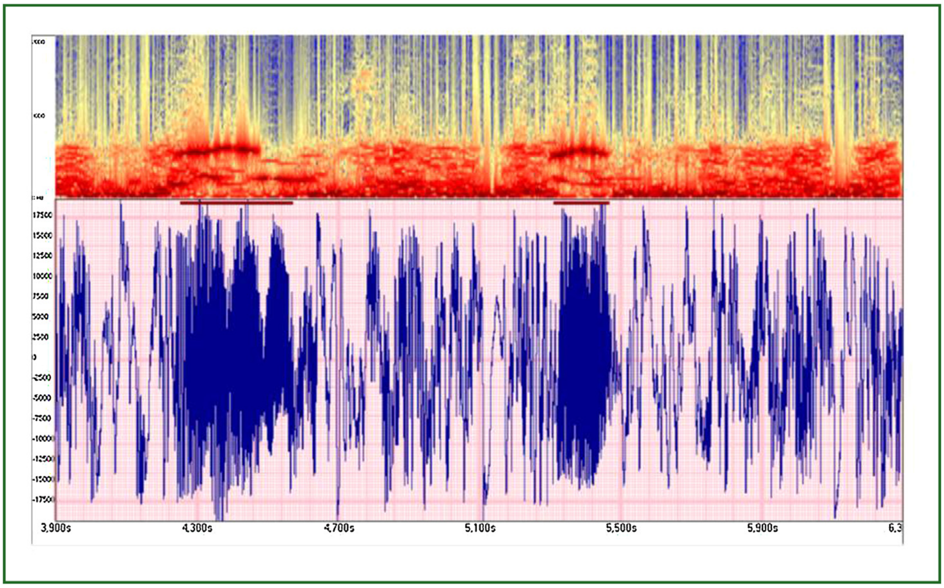

Figure A2. Wheeze detection in bronchiolitis record.
Sibilants dans le cadre d'une bronchiolite.

Disclosure of interest

The authors declare that they have no competing interest.

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