Robot-Based Tele-Echography
Clinical Evaluation of the TER System in Abdominal Aortic Exploration

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Objective. The TER system is a robot-based tele-echography system allowing remote ultrasound examination. The specialist moves a mock-up of the ultrasound probe at the master site, and the robot reproduces the movements of the real probe, which sends back ultrasound images and force feedback. This tool could be used to perform ultrasound examinations in small health care centers or from isolated sites. The objective of this study was to prove, under real conditions, the feasibility and reliability of the TER system in detecting abdominal aortic and iliac aneurysms. Methods. Fifty-eight patients were included in 2 centers in Brest and Grenoble, France. The remote examination was compared with the reference standard, the bedside examination, for aorta and iliac artery diameter measurement, detection and description of aneurysms, detection of atheromatosis, the duration of the examination, and acceptability. Results. All aneurysms (8) were detected by both techniques as intramural thrombosis and extension to the iliac arteries. The interobserver correlation coefficient was 0.982 (P < .0001) for aortic diameters. The rate of concordance between 2 operators in evaluating atheromatosis was 84% ± 11% (95% confidence interval). Conclusions. Our study on 58 patients suggests that the TER system could be a reliable, acceptable, and effective robot-based system for performing remote abdominal aortic ultrasound examinations. Research is continuing to improve the equipment for general abdominal use. Key words: abdominal cavity; aorta; remote operations; ultrasound.

Ultrasound imaging is a key imaging modality because of its convenience and noninvasiveness, but it requires a specialist to be with the patient to perform the examination. This could be problematic for small health care centers and isolated locations. Tele-echography and robot-based echography could be solutions for providing ultrasound imaging capabilities to these locations.

A pure telemedicine project such as the European Union TeleInViVo project still requires a specialist to move the probe, although an expert can provide an opinion remotely. Another type of project automates an echographic examination by using a robot. Finally, a third category of robot-based systems enables remote examination of patients by an expert who is not on-site. The system described here comes within this third category like the system used by Arbeille et al. It includes force feedback. This study aimed to show that the TER system was clinically effective under real conditions of use.
Materials and Methods

Study Population

From March 2004 to March 2005, 58 patients were included by 2 centers separated by 1000 km. Any patient with an abdominal aortic aneurysm (AAA) or atherosclerosis could be included. Neither the method used for diagnosis (eg, computed tomography, ultrasound, or clinical examination) nor the operator who carried out the examination was used as a criterion for inclusion. To have more realistic conditions, no exclusion was made on the basis of age or morphologic type. Pregnant women were excluded. All patients signed a consent agreement after being clearly informed of the aim and the modalities of the protocol, in conformity with bioethics laws. The protocol received the agreement of our national Health Committee.

Robot-Based Tele-Echography

The goal of this study was to evaluate the master-slave robotized system called TER on clinical points to show the feasibility, reproducibility, and sensitivity of a remote ultrasound examination. We focused on the detection of abdominal aortic aneurysms (AAAs) and iliac aneurysms. This system has already been described in the literature. It is a 2-part system with a master site and a slave site. In this study, an experimental network was used.

The Master Site

The master site is the location of the physician during the examination. It is composed of a computer connected to a virtual ultrasound probe. This virtual probe is placed on a haptic control system to control the real probe. This haptic control integrates a PHANTOM device (SensAble Technologies, Inc, Woburn, MA), which has 6 degrees of freedom and renders 3-dimensional force information. Position and orientation tracking of the virtual probe is performed within a work space of 16 x 13 x 13 cm and with a maximum force of 6.4 N. Information on the movement of the virtual probe is sent to the slave site to move the real probe. The physician watches the continuous ultrasound image flow sent by the slave site and can talk and listen to the slave site (Figure 1). A webcam is also connected. Multiple data are visible on the screen of the master site (Figure 2): the ultrasound image, real-time force feedback information, a virtual geometric model of the patient, views of the operator at the master site and the examination room (sent by webcams), and information on the network status (eg, transfer rates and connection status).

The Slave Site

The slave site is composed of the robot and the ultrasound device (Figure 3).

The Robot—The slave robot is a parallel uncoupled robot based on 2 independent structures dedicated to gross- and fine-positioning movements. Flexible cables are used to position and orient the ultrasound probe. The cables are connected to electrical motors. The translation movements on the surface of the body are controlled by 4 identical electrical motors connected by straps to a metal ring supporting the second parallel structure, as shown in Figure 4. The second parallel structure enables 3-dimensional orientation and translation along the z-axis of the ultrasound probe. Both subsystems can be controlled simultaneously.

The robot is controlled by a computer, which sends and receives data to and from the master site. A webcam and a microphone are also connected. Images from the ultrasound system are received by the computer and sent to the master site.
site. Information on the screen of the slave site is similar to what is rendered at the master site.

The Ultrasound System—Two different systems were used at each site: a TITAN system (SonoSite Inc, Bothell, WA) with a 3- to 5-MHz probe was used at 1 site, and an HDI 5000 system (Philips Medical Systems, Eindhoven, the Netherlands) with a 3- to 5-MHz probe was used at the other site.

The Network
The TER system used a VTHD (Vraiment Très Haut Débit) network during experiments. This is a very high-speed experimental communication network created and supported by France Telecom with data rates of 1 gigabit per second between the 2 sites.

Description of Examinations
A single-blind protocol was used. A physician scanned a patient, and a second physician repeated the ultrasound examination with no information on the patient. The second operator used the same ultrasound system with the same probe but with the remote TER system instead of the normal examination procedure. There was no operator present during the remote examination. A second person was present at the slave site during the TER examination to help set up the patient, install the robot, and use the ultrasound system (taking measurements, freezing the image acquisition, and adjusting image parameters). Although this person had to be familiar with the use of the ultrasound and TER systems, he or she could not comment or give medical advice during the examination. Depending on the day, this person was a nurse, a resident, or a physician, present to monitor the patient during the procedure.

Exploration of the abdominal aorta and common iliac arteries was chosen because it provided the opportunity to explore a diffuse disease with multiple aspects (atheromatosis) and a focal disease (AAA). Thus, qualitative and quantitative data could be evaluated.

For each examination (at the bedside and remotely), the following information was noted in the protocol register:

Figure 3. Slave site.
1. Evaluation of the atheromatosis. Three stages could be noted: none, segmentary, and diffuse.
2. The presence of an AAA and, if present, the maximum anteroposterior diameter and the presence or absence of intramural thrombosis.
3. The anteroposterior diameter of each primitive iliac artery.
4. Evaluation of the examination with 3 score values ranging from 0 to 100. The first 2 were for the operator and concerned the feasibility and global quality of the examination. The third value was for patient acceptance of the procedure.

At the end of the study, the right renal diameter was also recorded.

The classic method of examination (at the bedside) was used as the reference standard during this study. Images of all measurements were stored.

Data are represented by median and range or percentage. The reproducibility of quantitative data was assessed by calculating interobserver correlation coefficients and relative errors. The reproducibility of the qualitative data was assessed by calculating the $\kappa$ statistic. We used Stata 9 software (StataCorp, College Station, TX) for statistics.

Results

Population Study
Fifty-eight patients (42 male and 16 female) were included from March 2004 to March 2005. Fifty-four examinations (93.1%) were completed. The 4 failures included 2 dysfunctions of the haptic device, 1 connection problem with the VTHD network, and 1 computer crash at the slave site.

The median age was 63 years (range, 27–83 years). The median body mass index (weight/height$^2$) was 24 (range, 16.5–34.7), with 16 patients (30%) overweight (25 < body mass index < 30) and 5 (9%) obese.

Aneurysms
Eight patients of the 54 who had a complete examination had an AAA, for an AAA prevalence rate of 15%. The average anteroposterior diameter was 6.5 cm (95% confidence interval, 3–17 cm), and the median was 5.4 cm.

All aneurysms were diagnosed by both methods, as were the 6 cases of intramural thrombosis and the 4 extensions to the iliac arteries.

Evaluation of Atheromatosis
The conventional examinations found 14 patients without atheromatosis, 11 with segmentary lesions, and 28 with diffuse atheromatosis. The $\kappa$ value was $84\% \pm 11\%$ (95% confidence interval). The mismatches included 4 diffuse forms graded as segmentary, 2 segmentary forms graded as normal, and 1 segmentary form graded as diffuse.

Diameters

Aorta
The interobserver correlation coefficient was 0.982 ($P < .0001$). The difference in measurements was less than 4 mm in 52 cases (96.3%), between 4 and 10 mm in 1 case (1.9%), and greater than 10 mm in 1 case (1.9%). The median relative error was 0% (Figure 5). The maximum and minimum relative errors were 34.5% and −26.1%. Concerning the measurement errors, 50% were less than 5%, and 80% were less than 15%.

Figure 5. Relative errors of aorta diameters.
Common Iliac Arteries
The interobserver correlation coefficient was 0.760 \( (P < .0001) \). The median relative error was –4%. The maximum and minimum relative errors were 27.5% and –64.1%.

Examination Duration and Global Satisfaction
The median duration ± SD increased from 12 ± 7 minutes for the classic ultrasound examination to 17 ± 8 minutes for the remote examination on a \( t \) test for repeated measures \( (P < .001) \). Evaluation scores for the global quality of the examination were 75.6 ± 15 \( (P < .01) \) for the remote examination and 87 ± 12.5 \( (P < .01) \) for the classic examination. The patients evaluated the acceptability at 84 ± 18 with a median of 90. Two patients gave a score of less than 50.

Discussion
We collected clinical data on a new use of a well-known radiologic modality. We selected a disease that allowed us to explore 3 types of echographic data (qualitative, quantitative, and semiquantitative).

We achieved remote vascular exploration in nearly every case, and we were able to explore every objective for each patient. The failures occurred at the beginning of the study and were mainly caused by the immaturity of this prototype system.

The exploration was limited to the main vascular structures of the abdomen and pelvis, but TER performed well in exploring an ideally placed structure such as the aorta and a more lateral structure such as the common iliac artery. An examination of the entire abdominal cavity seems more difficult. In fact, assessment of the convex lateral zones is more challenging because the robot is unable to explore the flanks with the patient in the supine position. Patients must therefore be positioned on their side. The tension on the probe may be too high and therefore does not permit an optimal examination of the kidneys and spleen. Consequently, since the completion of this study, we have raised the height of the motors. Preliminary tests with this setup seem to result in a much more satisfactory outcome. In addition, exploration of these zones was not the object of our study. Another study is needed to evaluate that point.

Every AAA present was diagnosed. The remote measurements were reliable. The greatest discrepancy between the remote and classic examinations occurred for the patient with the largest aneurysm (17 cm in anteroposterior diameter), with a relative error of 11%. The interobserver variability was good in comparison with data from the literature.\(^{11,12}\) Although the reproducibility of the measurements was better for the aorta than for the iliac arteries, the absolute value for this difference was minimal.

In evaluating atheromatosis, the remote examination remained sensitive. At no point was a difference of greater than 1 level recorded. We assume that some of the errors stemmed from the definition of levels. A fourth level between the second and third would have been useful.

The remote examination was slightly longer, but the durations of both procedures increased equally in a difficult examination situation. The practice of using the TER system seems to play an important role in the feeling of confidence in the examination. This is also a major point for the local practitioner’s overall satisfaction. In fact, this satisfaction decreased significantly with the remote examination, although nothing objectively proved that the remote examination was less effective than the bedside procedure.

The patients reported a very high satisfaction level. The 2 patients who gave a low score had an examination with a technical problem (among the 4 failed procedures).

The TER system can explore a large area, but it may be harder to use over convex surfaces. The telemedicine systems using pure video transfers such as TeleInViVo are less appropriate for ultrasound exploration than TER because an expert is needed to carry out the examination; moreover, specifying probe motion remotely to the operator by oral orders may be difficult and nonintuitive. Another approach to robot-based teleechography is illustrated in the OTELO (mobile tele-echography using an ultralight robot) system,\(^{4–6}\) which can explore only a small zone at a time and requires someone to move the system frequently to another zone, although this is done easily whatever the location. Having to reposition the system by hand may be an obstacle for easy clinical use. We should nevertheless point out the fact that the use of the TER system does...
require the presence of somebody at the remote site who is able to position the patient correctly and who is aware of the basic functioning of ultrasound equipment. However, this education of the remote assistant is very quick and easy.

Today, the TER system remains the only procedure that has been clinically evaluated using appropriate methods. The other studies\textsuperscript{4–6} were designed to evaluate the feasibility of the examinations but not their sensitivity and specificity in detecting a disease in real patients, whatever their weight, age, or echogenicity. Those studies compared the ability of the robotized examination to visualize organs well but never tested its real efficacy. Our system showed good results for qualitative variables (atheromatosis, aneurysms, and intramural thrombosis) and quantitative data (diameters).

In conclusion, we have shown that a remote examination with the TER system is possible as an everyday examination to detect, measure, and describe an AAA or an iliac aneurysm. In our limited study on 58 patients, compared to the bedside examination, it appears to be as sensitive, and the measurements seem reliable. However, many more cases will be necessary to fully demonstrate those points and to address safety. Another study has begun to determine whether these results can be extended to exploration of the entire abdominal cavity in an emergency unit.

References


