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Fetal tele-echography using a robotic arm and a satellite link

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KEYWORDS: echography; fetal growth; fetus; satellite; tele-medicine

ABSTRACT

Objective *To design a method for conducting fetal ultrasound examinations in isolated hospital sites using a dedicated remotely controlled robotic arm (tele-echography).*

Methods *Tele-echography was performed from our hospital (expert center) on 29 pregnant women in an isolated maternity hospital (patient site) 1700 km away, and findings were compared with those of conventional ultrasound examinations. At the patient site, a robotic arm holding the real ultrasound probe was placed on the patient's abdomen by an assistant with no experience of performing ultrasound. The robotic arm, remotely controlled with a fictive (expert) probe, reproduced the exact movements (tilting and rotating) of the expert hand on the real ultrasound probe.*

Results *In 93.1% of the cases, all biometric parameters, placental location and amniotic fluid volume, were correctly assessed using the teleoperated robotic arm. In two cases, femur length could not be correctly measured. The mean duration of fetal ultrasound examination was 14 min (range, 10–18) and 18 min (range, 13–23) by conventional and tele-echography methods, respectively. The mean number of times the robotic arm was repositioned on the patient's abdomen was seven (range, 5–9).*

Conclusion *Tele-echography using a robotic arm provides the main information needed to assess fetal growth and the intrauterine environment within a limited period of time. Copyright © 2005 ISUOG. Published by John Wiley & Sons, Ltd.*

INTRODUCTION

Telemedicine has the potential to become a powerful tool, especially in developing countries or areas with reduced medical facilities. In some African regions, for example, more than 75% of the population may be at more than a day's travel from the nearest hospital[1]. Even in high socioeconomic countries, small medical centers do not necessarily have sonographers available 24 h a day for initial diagnostic imaging in emergency cases. One of the major advantages of ultrasound imaging in medicine is the possibility to evaluate the degree of emergency of a patient's condition quickly and non-invasively. In a pregnant woman, even a basic fetal examination can provide valuable information. In areas with reduced medical facilities, well-trained sonographers are not available and transferring the patient to a center with good facilities may be problematic or expensive.

We have previously presented a new technique for teleoperating ultrasound examinations in adult patients using a dedicated low-weight portable robot[2]. The robotic arm consisted of an electric motorized support holding a conventional two-dimensional (2D) ultrasound probe, which was able to orientate the probe on the patient's skin surface in all directions and reproduce all the movements of an expert hand until the appropriate view of the organ under investigation was found. The project originated from the Unité de Médecine et Physiologie Spatiales (UMPS), Université Hôpital Trousseau, Tours, France, who designed the concept and the technical requirements for the robot. The Laboratory of Vision and Robotics (LVR) from the university developed the prototype (Patent 9903736).

The objective of this preliminary study was to design and evaluate a new method for teleoperating fetal ultrasound examinations in pregnant women in an isolated place, with an assistant unfamiliar with performing ultrasound (non-sonographer), a robotic arm, and a connection with a satellite link to a site with experienced personnel and high-quality facilities (expert site).

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METHODS

Robotic design

Principle of the system

At the isolated site (patient site) the robotic arm, on which the ultrasound probe is fixed, is handled by a non-sonographer (doctor, paramedic). At the expert site, a sonographer moves a fictive probe (expert probe) which is connected to a computer (Computer 1). This expert probe simulates the ultrasound probe. Computer 1 sends the coordinate changes induced by the expert probe movements to the computer located at the patient site (Computer 2) via an ISDN (terrestrial telephone line) connection or a satellite link. Computer 2 controls the robotic arm, which reproduces the movements of the expert probe in the ultrasound probe positioned on the patient's abdomen. The robotic arm reproduces exactly the movement of the sonographer's hand who guides the examination from the expert center. At present, the expert cannot take over the probe holder to move the probe support above the maternal abdomen through the computer command; the assistant at the patient site moves it, based on vocal instructions given by the expert using video controls[3] (Figures 1 and 2).

Probe holder

The probe holder is held within a frame, with a ring (7 cm in diameter) at the base that is kept in contact with the patient's skin by the assistant who provides a stable contact. In order to be able to visualize most fetal organs, including the fetal heart, the system was designed for optimal use with sector scan probes (mechanical oscillating probe, electronic curved- or phased-array probe). The system uses probes for detection of superficial (5–10 MHz) and deep (2–5 MHz) organs, and uses probes of various shapes and sizes up to a maximum body probe diameter of 40 mm. The probe head width is limited by the diameter of the ring applied to the patient's skin. The weight of the probe holder (2.5 kg) applies a pressure that ensures contact between the skin and the probe. The expert can apply additional pressure, limited to 15 N, by pushing on the expert probe, with the maximal displacement of the probe through the ring being 1.5 cm. Such an option is particularly useful when the probe is applied to irregular surfaces like ribs and some abdominal areas. Because of the very limited pressure applied and the short probe displacement there is no need for feedback control of the force applied to the probe.

Communication

The video (patient and expert views) exchanged between the two sites, the dynamic ultrasound images sent from the patient site to the expert site, as well as the command orders sent from the expert to the patient site for activating the robot movement, were transmitted through Eutelsat W1 (V SAT Protocol; Eutelsat, Paris). Both sites were equipped with a parabolic antenna of 1.2 m, an emitter-receiver module and four ISDN telephone lines as a back-up communication link, including one channel of 128 Kbit/s for robotic movement orders and three others of 384 Kbit/s for the video images. The time delay between the expert probe motion and receiving the video image at the expert site was less than 0.5 s with an ISDN connection and around 1 s with satellite lines.

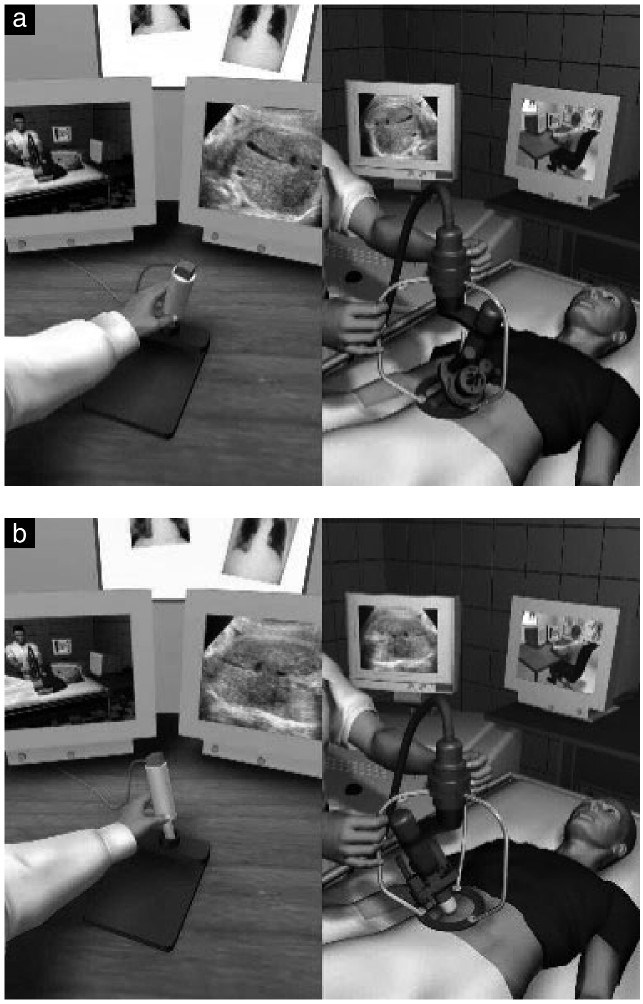

Figure 1 Pictures showing the expert on the left manipulating the fictive expert probe and the patient on the right with the robotic arm positioned on the body by a non-sonographer. (a) When the expert moves his probe to the right, the robotic arm orientates to the right. (b) When the expert moves his probe to the left, the robotic arm orientates to the left.

Patients

The pregnant women were recruited between May 2004 and July 2004 in Ceuta (a Spanish city in north Morocco, 1700 km from our university hospital), from outpatients attending for a routine ultrasound scan as part of a screening program, or because they were high-risk pregnancies. The research protocol was validated by the health committee of our state (Comite Consultatif pour la Protection des Personnes en Recherche Bio-medicale (CCPPRB), no. 2002/07) and by our university hospital

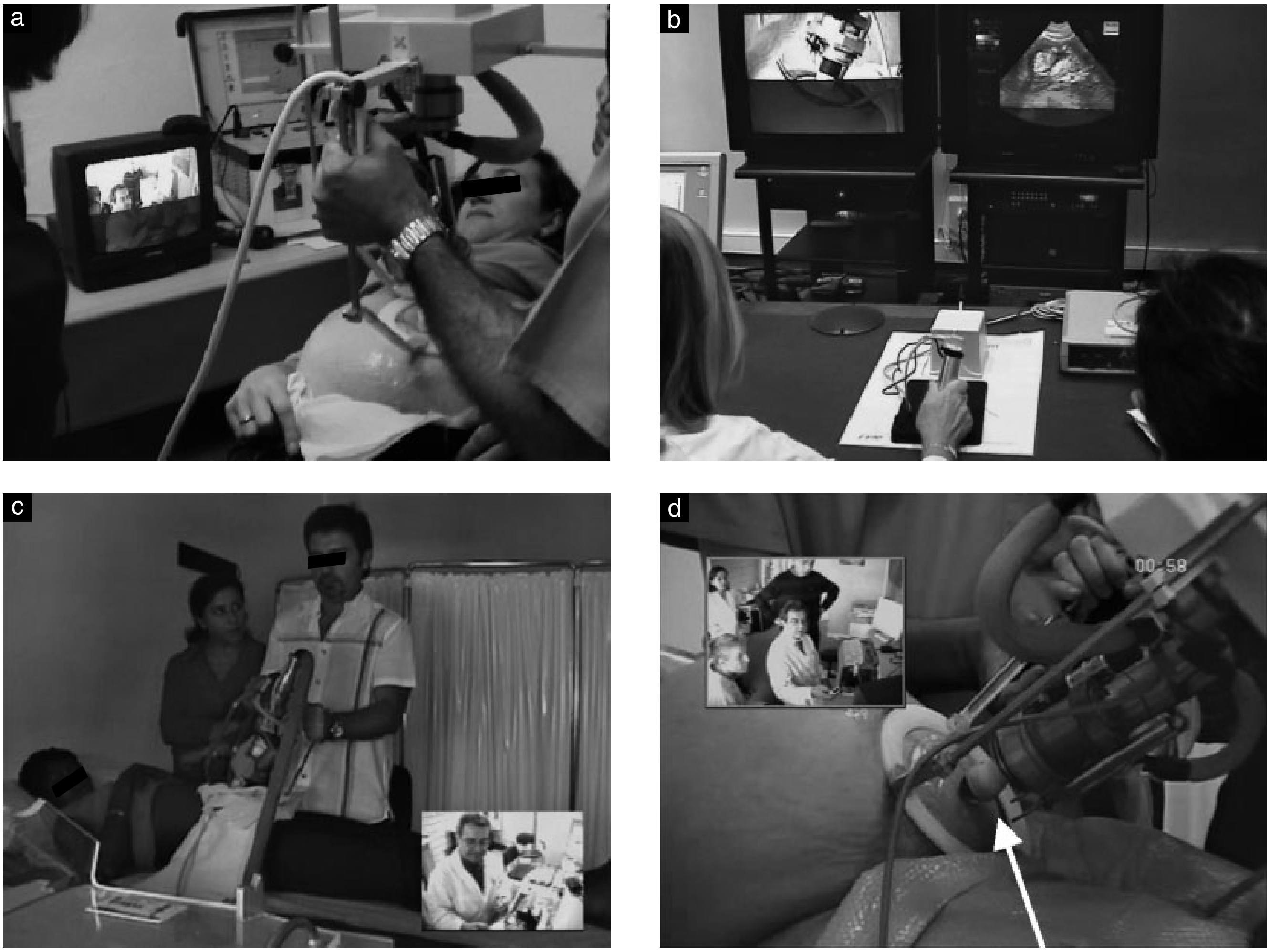

Figure 2 Photographs showing views of the expert and patient centers. (a) The robotic arm is shown being positioned on the patient skin. The TV monitor displays a view of the expert at the expert center. To the right of the TV monitor is the electronic box, which controls the robot movements. (b) A view of the expert center with the expert probe and two video screens for direct visualization of the robot placement on the patient (left screen), and the fetal ultrasound view (right screen). (c) Photograph showing the robotic arm being held by the future father, and a view of the expert is shown in the bottom right corner. (d) A view of the robotic arm located at 6 h (between the umbilicus and pubis). The echographic probe is marked with an arrow.

and the isolated maternity hospital. All patients were informed about the entire protocol and signed an informed consent form.

Tele-echography procedure

At the patient site, a non-sonographer was present who held the robotic arm and placed it according to the requests of the expert. At the expert site, located at our university hospital, the sonographer firstly guided the placement of the robotic arm on the abdomen of the pregnant woman and secondly, teleoperated the robotic arm (holding the echo probe) by moving the expert probe.

The positioning of the probe holder (robot) was controlled in real time by the expert using video images transmitted from the isolated site to the expert site by videoconferencing. During this phase, the expert had a real-time video of both the patient (anatomical parts to be investigated) and the probe holder position, and also an audio link with the non-sonographer assistant and the patient (Figure 2b). In order to improve the precision of movement applied to the real probe, the fictive probe head was fixed on the table at the expert center.

The real probe initially had to be oriented perpendicular to and in contact with the skin while moving it slowly around the umbilicus at a distance of 5–10 cm. Areas around the umbilicus were identified as hours on a clock, with the center as the umbilicus (12 h: between umbilicus and sternum; 6 h: between umbilicus and pubis; 3 h left horizontal umbilical line) (Figure 2c). The expert asked the assistant to position the probe head (i.e. acquisition plane) in an orientation that was defined as the reference position. When the assistant had correctly positioned the robotic arm on the desired area (so the expert could at least see part of the organ to be examined), the expert asked the assistant to adjust the ultrasound settings (gain, depth) and ensure the robotic probe holder remained motionless. The expert could then search for the ultrasound view needed for examination and diagnosis by tilting, rotating and applying pressure to the expert probe and analyzing the ultrasound images received in real time (Figures 3– 7). When the expert was unable to obtain the appropriate view to measure, for example, the biparietal diameter, transverse abdominal circumference or femur length, he could ask the assistant to move the robotic system a few cm right, left, up or down, as necessary.

A subsequent conventional ultrasound scan performed by another expert sonographer at the local hospital in Ceuta was then performed.

Study protocol

The objective was to test the ability of tele-echography to perform a basic fetal ultrasound examination. The head, heart, abdomen, legs, placenta and amniotic fluid were assessed in longitudinal and transverse cross-sectional views by both robotized and conventional ultrasound (Figures 3–7). Quantitative parameters included biparietal diameter, abdominal diameter and femur length.

Figure 3 Ultrasound image showing the biparietal view with the cerebral peduncle.

Figure 4 Ultrasound image showing the abdomen and femur in cross-sectional view.

Figure 5 Ultrasound image showing the straight echogenic line of the fetal femur.

Figure 6 Ultrasound image showing the cardiac four-chamber view.

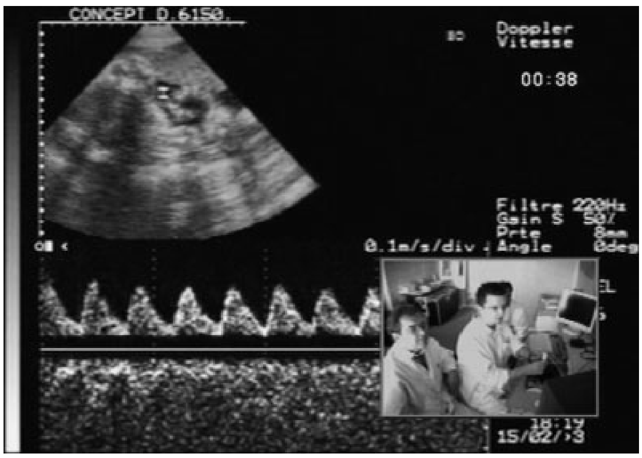

Figure 7 Doppler ultrasound image showing the velocity spectrum of the umbilical artery.

Qualitative parameters included placental echogenicity (normal or heterogeneous) and insertion (fundal, lateral, low), and amniotic fluid volume (normal, low, high). The ability of the system to visualize the organs entirely was evaluated using a visualization score (number of cases with all items correctly visualized/total number of cases). For fetal biometric parameters, total agreement between teleoperated and conventional ultrasound scans was considered to have been achieved if the difference in measurement was less than 5%. In our study, we limited the time allowed to assess each item to 5 min. The number of times the robotic probe holder was repositioned and the total duration of the examination were recorded.

RESULTS

In our study, 29 pregnant women were recruited and had both teleoperated and conventional ultrasound examinations. Among these patients 20 were 'normal' pregnancies (i.e. low risk) and nine were high risk (pre-eclampsia $n = 4$; intrauterine growth restriction (IUGR) $n = 5$). Mean gestational age at examination was 34 (range, 30–38) weeks. The audio, video and robot control information were transferred between the patient and expert sites using the Eutelsat W1 satellite link. Minimal bandwidth (200 Kbit/s) and frame rate (15/s) were sufficient to provide real-time interaction between the two sites and guarantee an image quality adequate for interpretation. The expert (radiologist, obstetrician, midwife) needed no more than 1 h to become familiar with the system. All patients gave their consent and none had any complaints about the system. The time delay between the activation of the expert probe and the returned ultrasound image was around 1 s. The ultrasound machines used were a Sonosite 180 (Sonosite, France) and a GE 400 (GE Medical Systems, Spain) equipped with a 3.5 phased- or curved-array probe.

The satellite communication and robot activation set-up took 10–15 min depending on the availability of the requested data flow and image frame rate through the satellite network. In two cases we had to restart the system and delay the teleoperated investigation by a few minutes. In one case, the investigation was delayed by 15 min due to satellite communication problems. We never had to stop the examination once initiated and the image quality always remained acceptable for diagnosis. The four ISDN lines (384 Kbit/s) were successfully used in three additional cases to check that the network was adapted to the teleoperated echography. The pressure applied on the skin by the robotic arm in relation to its weight (2.5 kg) and the possibility to apply an additional pressure of 15 N for moving the probe along its own axis by $\pm$ 1.5 cm were sufficient for maintaining good contact with the skin.

Fetal presentation, placental location and echogenicity, and amniotic fluid volume were always concordant between the teleoperated and conventional ultrasound scans. The visualization score was 93.1%, i.e. in 93.1% of the cases all items were correctly visualized and the biometric parameters were in agreement with the conventional subsequent ultrasound measurements. In two cases (36 and 37 weeks' gestation) femur length could not be correctly evaluated within the allotted 5-min scanning time.

The mean total duration of a fetal teleoperated ultrasound examination was 18 min (range, 13–23), and the mean number of times the robotic arm was repositioned on the patient's skin was seven (range, 5–9). The mean duration of the conventional ultrasound examination was 14 min (range, 10–18). The four-chamber view of the fetal heart was visualized in all cases. The umbilical Doppler recordings were attempted and successfully performed in five cases. However, the four-chamber view and umbilical Doppler recordings were not taken into account in the evaluation of the visualization score.

DISCUSSION

Our study demonstrates the potential of tele-echography to assess fetal growth and detailed anatomy. The expert remote from the examination site was in control of the probe held by an assistant on site through the robotic arm and satellite link. This experiment followed our failed and unpublished attempts to guide a non-qualified assistant to scan both by bedside advice and also by video and audio guidance when the examination was attempted in the Russian Mir space station. We therefore developed a teleoperated ultrasound probe attached to a robotic arm held over the patient's abdomen by a non-ultrasound-trained assistant, while the ultrasound probe movements were under the remote control of the expert hand[2]. The assistant did not manipulate the echographic probe at all after correctly positioning the robotic arm on the desired area. The videoconference link allowed the patient and the expert to have a dialogue throughout the examination.

Robotic-surgery is probably the most popular application of robotics in medicine[4–6]. However, the comparison with telesurgery is difficult because the rationale is different. The surgical robotic arm is supposed to reproduce very accurately the complex movements of the surgeon's hands. The robot must explore the three directions of space (six degrees of liberty), whereas the echographic robotic arm has to orientate the probe head on the patient's skin at up to 45 degrees around its own axis, which was sufficient to obtain all requested images. This contact, however, depends upon an assistant on site, thus limiting the risk of injury to the patient. A satellite link appears suitable for the use of the echographic robotic arm because temporary interruption of the data transfer does not carry potentially dramatic implications as it does for the surgical robot.

The ultrasound images obtained made it possible to evaluate the fetal presentation, biometry of the fetal head and abdomen both in diameter and circumference measurements as well as the femur length, and the anatomy of the four chambers of the fetal heart, brain, spine and kidneys. The placenta, cord insertion and amniotic fluid volume could also be assessed. Such observations should be sufficient to address most ultrasound screening issues in relation to gestational age determination, fetal growth, including umbilical Doppler recordings, placental location and fetal anomalies.

In 93.1% of the cases, all ultrasound features could be investigated although not more than 5 min were allocated to the expert for each item. This high score confirms that the remote control of an echographic probe through a robotic arm and a satellite network reliably allows a full fetal ultrasound examination to be performed safely.

The duration of the fetal teleoperated ultrasound examination was approximately 30% longer than that by conventional sonography because it involved repositioning the robotic arm. However, the duration of the examination was acceptable for both routine and emergency use.

Conventional 2D real-time and Doppler ultrasound scans are operator-dependent because a tilt or rotation of the probe of a few degrees is sufficient to obtain or lose the necessary view for reliable diagnosis. Thus, in the absence of a correctly trained operator by the side of the patient, it may be impossible to find the specific view needed for making fine measurements or to give an expert opinion on detailed anatomical structures.

The present preliminary study cannot provide a definitive conclusion on the potential and limitations of a robotic system as compared with other methods. The validation will be extended to a larger population of patients, and more sonographers will be trained to practice robotized tele-echography. Each emergency situation requires a quick and reliable diagnosis and as changes of a few degrees in the orientation of the probe can prove critical, we believe that the robotic arm system is the best adapted system available to date to provide patients living in isolated sites with the same diagnostic performance as that offered in hospitals where the experts are located. Robotized tele-echography may also serve as a screening tool in hospitals lacking facilities and personnel, from which a timely referral could then be made.

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