Advanced Ultrasound

in Diagnosis and Therapy
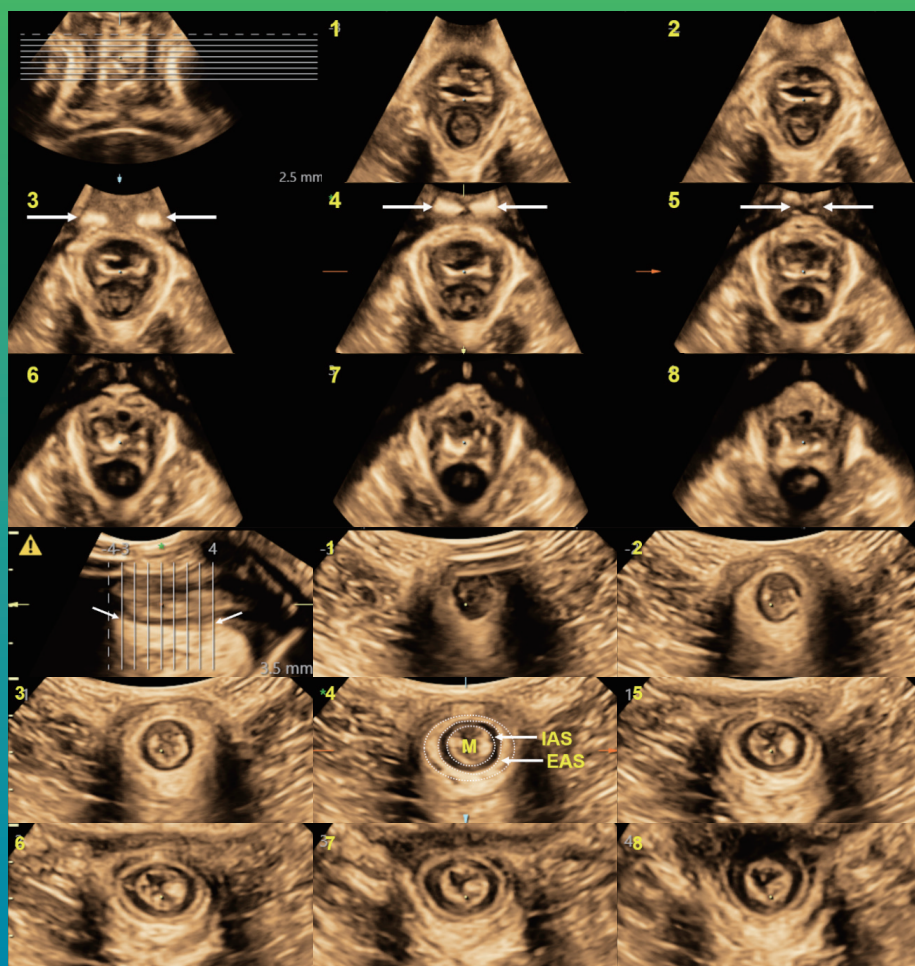
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Clinical Application of Robot-assisted Teleultrasound

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Abstract: With the development of network technology and intelligent robot technology, Robot-assisted teleultrasound has played an important role in clinical fields. The application of real-time remote ultrasound technology has made the ultrasonic diagnosis break through the limitation of time and space distance, and solved the problem of shortage of medical resources to a certain extent. This article introduces the development and application basis of robot-assisted teleultrasound, summarizes the clinical application status, and discusses the advantages and limitations of its current application. In addition, we discuss the value in application scenario, interventional therapy and intracavitary ultrasound in the future.

Key words: Teleultrasound; Robot; 5G; Remote medicine

Ultrasound is a non-invasive, flexible, and portable imaging technology that has been coined as the "Future Stethoscope" for over three decades [1], serving as the eyes of clinicians. Due to the advancement of ultrasound technology, there is a growing demand for ultrasound imaging, yet there is an insufficient number of sonographers to meet this demand. Moreover, the development of medical technology is unbalanced across different regions, paving the way for teleultrasound. Traditional teleultrasound involves the establishment of a consultation terminal (physician terminal) and a remote terminal (patient terminal), where ultrasonic images collected at the remote terminal are transmitted to the consultation terminal through the network. The experts of ultrasound at the consultation terminal then make a diagnosis and provide treatment based on the transmitted images.

The technology of teleultrasound was initially applied by NASA (National Aeronautics and Space Administration) in the International Space Station. With basic training, astronauts without medical backgrounds can perform musculoskeletal ultrasound and FAST (focused assessment with sonography trauma) under the guidance of ground experts [2]. The earliest civilian teleultrasound technology was primarily used in obstetric and cardiac ultrasound for newborns in remote areas, and it has gradually expanded to the field of pre-hospital emergency care [3-6]. The application of teleultrasound has alleviated the shortage of sonographers in regions with limited medical resources, enabling superior hospitals to offer high-quality medical resources to those in remote areas.

Traditional teleultrasound has its limitations. Firstly, there is a shortage of sonographers in grassroots units. Primary doctors may also have limited diagnostic skills, resulting in ultrasonic images that may not show the lesion site clearly and in a standard way at the remote end. Secondly, network limitations prevent real-time and high-definition transmission of ultrasound images. Furthermore, during large-scale public health events, traditional teleultrasound may not fully utilize its potential. For instance, during the COVID-19 pandemic, patients in isolation wards are often severely ill. Despite the use of protective suits, doctors have to operate ultrasonic instruments and gather images while being guided by senior doctors at the consultation end. This process is complex and inconvenient, thereby potentially delaying diagnosis and treatment. However, in recent

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years, with the advent of 5G technology and robot-assisted ultrasound, robot-assisted teleultrasound has emerged as a crucial aspect of teleultrasound medical services.

Basics of Robot-assisted Teleultrasound Application

Based on mobile communication technology, robot-assisted teleultrasound has the ability to overcome geographical barriers and provide patients with remote medical services, such as teleultrasound, diagnosis, and report delivery. The system mainly consists of a diagnostic terminal, a scanning terminal, and a remote data transmission module. The diagnostic terminal includes structural components, an operation control system, an audio and video system, and diagnostic software. The scanning terminal is composed of structural components, a motion execution system, an ultrasonic system, an audio and video system, and scanning software. Sonographers can remotely control the ultrasonic probe mounted at the end of the scanning arm in real-time, enabling real-time scanning of patients through manipulation of the contour probe. It provides a highly efficient and effective application of robotic technology in the medical field. During the examination, sonographers can communicate with the patient through a high-quality audio and video system, adjust the parameters of the ultrasonic equipment at the scanning terminal in real-time, and obtain real-time ultrasonic images for medical diagnosis.

The key technologies involved in robot-assisted teleultrasound are twofold. Firstly, there is the technology for robot-assisted ultrasound. Ultrasonic examinations require the robot arm to move the probe smoothly and flexibly to the ideal position. Therefore, the robot arm needs to have sufficient freedom of movement and it needs to be able to provide real-time feedback to the diagnostic terminal on the strength of the robot arm at the scanning terminal. This ensures that the operator can accurately control the amount of force applied to the patient. Martinelli et al. [7] conducted a study involving 58 patients with aortic and iliac aneurysms using a robot-assisted ultrasound with four degrees of freedom. The results showed a high level of consistency with conventional ultrasound findings. In 2015, Monfaredi et al. [8] developed a robotic arm with six degrees of freedom, enabling the mounted probe to be fully moved and oriented. The robotic arm also features a force sensor, ensuring safe and accurate robot-assisted ultrasound.

In addition, wireless transmission technology is a critical component of robot-assisted teleultrasound, providing real-time transmission of high-quality and non-destructive ultrasonic images, facilitating communication between the diagnostic and scanning terminals, and supporting continuous and smooth operation of the ultrasonic probe. Additionally, the technology must be capable of receiving pressure feedback information. In the past, wireless transmission technology was unable to handle the enormous data transmission required for real-time robot-assisted teleultrasound, resulting in slow transmission speeds and high time delays [9]. However, the emergence of 5G (5th Generation) technology has made the application of robot-assisted teleultrasound feasible, as its peak transmission rate can reach 10 GB/s and the delay time can be reduced to an imperceptible 1ms. As of now, China has successfully conducted robot-assisted teleultrasound examinations using 5G technology. On March 22, 2019, our team accomplished a ground-breaking achievement by performing the world's first robot-assisted teleultrasound examination, which spanned over 2,600 kilometers and enabled us to examine patients in Sanya and islands in the South China Sea from Beijing. Following this feat, we established the first-ever teleultrasound clinic based on 5G on April 17 of the same year [10], which signified the tangible advancement of robot-assisted teleultrasound based on 5G from the research stage to the clinical application stage.

The Clinical Application Status of the Robot-assisted Teleultrasound

Application of robot-assisted teleultrasound in lung and heart

Pulmonary ultrasound, also known as the "visual stethoscope" among physicians, is now widely utilized in clinical practice due to its numerous advantages, including convenience, ease of operation, lack of radiation, bedside capability, and repeatability [11]. The introduction of robot-assisted teleultrasound has made the technology even more accessible, overcoming geographic barriers and enabling physicians to diagnose lung conditions and assess cardiopulmonary function in patients residing in isolated areas with limited medical resources, including those residing in high-altitude regions.

Yun Zhang et al. [12] conducted teleultrasound examinations on 27 patients with clinical symptoms of high altitude pulmonary edema in Naqv, Xizang Province using robot-assisted teleultrasound. The results demonstrated that this technology could effectively detect ultrasonic manifestations of high altitude pulmonary edema, such as pleural thickening, B-line increase, lung consolidation, pleural effusion, and the

results were consistent with lung CT diagnoses. This confirms the potential of remote ultrasonic robots in diagnosing pulmonary edema and offers a solution for remote areas with limited medical resources [13-14]. It is believed that robot-assisted teleultrasound can help overcome the shortage of sonographers in remote areas and promote balanced development of medical services. Additionally, the robot-assisted teleultrasound can replace sonographers in entering plateau areas and reduce the risk of high altitude pulmonary edema for ultrasound workers (Fig. 1).
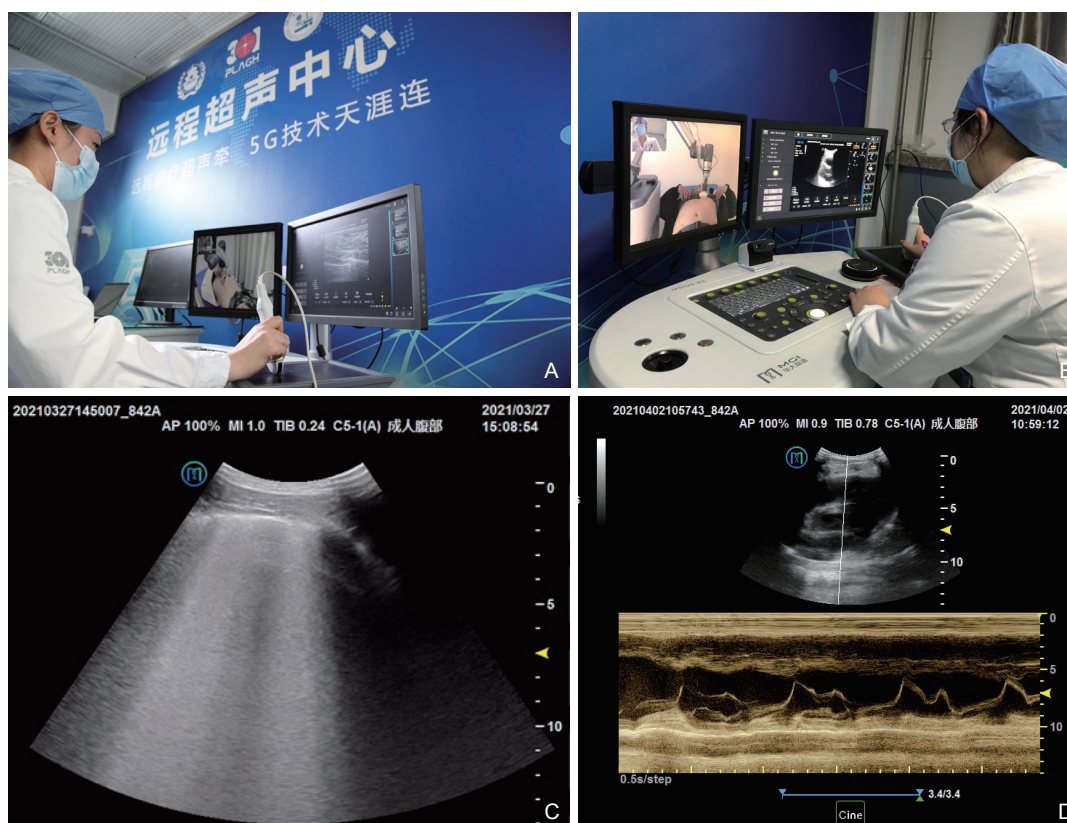
Figure 1 Application of robot-assisted teleultrasound in lung and heart. (A) Robot-assisted teleultrasound in lung of diagnostic terminal in patients with high altitude pulmonary edema; (B) Robot-assisted teleultrasound in cardiac of diagnostic terminal in patients with high altitude pulmonary edema; (C) Robot-assisted teleultrasound images of the lung in patients with high altitude pulmonary edema; (D) Robot-assisted teleultrasound images of the cardiac in patients with high altitude pulmonary edema.

At the end of 2019, an outbreak of novel coronavirus infection occurred, and due to the high infectivity of the disease, suspected or confirmed patients were required to be medically quarantined. As patients in isolation wards were congested, lung CT examinations were not possible, and thus, bedside ultrasound became an important means for dynamic imaging diagnosis [15-16], disease change detection, and efficacy evaluation of patients with novel coronavirus pneumonia. However, sonographers performing bedside ultrasound were at risk of infection, and there was a shortage of sonographers. During this period, some scholars tried to use a robot-assisted teleultrasound to conduct remote examinations and consultations on confirmed or suspected patients with novel coronavirus pneumonia in isolation wards in two different cities. They successfully completed lung ultrasound examinations and cardiac echocardiography and assessed the patients' cardiopulmonary function. The examination results were highly consistent with those of lung CT and bedside ultrasound [17]. Shengzheng Wu and others also used a remote ultrasonic robot to evaluate the cardiopulmonary function of patients in isolation wards separated by more than 1400 kilometers [18]. Through these studies, it is confirmed that the remote ultrasonic robot can break through the limitations of time and space, provide a new image diagnosis mode for patients in the isolation ward of public health emergencies, "send" the services of professional sonographers to the isolation ward of infectious diseases, and significantly reduce the exposure of sonographers in the epidemic area, thus avoiding cross-infection.

Application of robot-assisted teleultrasound in abdomen

Acute abdomen is a common emergency that presents

with sudden onset, severe symptoms, and rapid changes in the patient's condition. Early diagnosis is crucial for timely treatment. Ultrasound examination is widely recognized as an essential tool for diagnosing acute abdomen [19-22]. However, in remote areas, primary care facilities, and large-scale public health events, where resources are limited, or sonographers are scarce, patients with acute abdomen often need to be transported to higher level hospitals, leading to delays in treatment and even life-threatening situations. Fortunately, the use of robot-assisted ultrasound can identify the cause of acute abdominal disease. This technology allows for some patients to be treated on-site with ultrasound guidance, some to be promptly evacuated, and others to avoid unnecessary transportation and evacuation by ruling out acute abdominal disease. In this way, a hierarchical diagnosis and treatment approach can be implemented.

During the novel coronavirus infection epidemic, Hangjun Chen et al. [23], used the robot-assisted to examine the abdomens of 30 patients infected with novel coronavirus in isolation wards and compared the results with bedside ultrasound examination. The results showed that the remote ultrasonic robot was able to clearly display common lesions of various abdominal organs, and the quality of the images collected and the diagnosis based on those images were consistent with the results of routine bedside ultrasound examination, according to the standard section of the Zhejiang Ultrasonic Medical Quality Standard guidelines [24]. As a result, it was concluded that the robot-assisted teleultrasound can replace conventional bedside ultrasound in the assessment and diagnosis of patients in isolation wards. In another study, Keyan Li et al. [25] conducted robot-assisted teleultrasound examinations on 44 patients with acute abdominal pain at Sansha People's Hospital on Yongxing Island. The robot-assisted teleultrasound was able to accurately display common abdominal organ inflammatory changes and calculi. Compared with the results of revisit or disease outcome, the diagnosis efficiency was high, leading the authors to suggest using robot-assisted teleultrasound for on-site evaluation of acute abdomen in areas with relatively scarce medical resources, such as islands.

Application of robot-assisted teleultrasound in limb and soft tissue

Sports injuries refer to a variety of injuries caused by external forces during human movement, which are commonly seen in high-intensity military training and sports. They mainly involve injuries to the musculoskeletal joints and soft tissues of the limbs. Data shows that the incidence rate of military training injuries is between 7.9% and 47.3% [26], and that the quality of life and training for injured soldiers is reduced, which can affect combat effectiveness. A survey of training injuries in a ministry from 2015 to 2019 showed that 25.4% [27] of the injuries were soft tissue injuries. MRI is the most valuable tool for diagnosing soft tissue injuries, but it is difficult to use in grassroots units and is time-consuming and expensive. However, the value of high-frequency ultrasound in the diagnosis and treatment of sports injuries has been increasingly prominent [28]. The robot-assisted ultrasound can also be used to examine and evaluate limb muscle, bone, joint, and soft tissue injuries, overcoming the current lack of specialists in primary medical units and the low level of muscle and bone ultrasonic diagnosis. Zhaoming Zhong et al. [29] conducted robot-assisted teleultrasound examinations on 58 patients with limb pain or paresthesia in a training base and diagnosed various musculoskeletal injuries such as joint effusion, ligament injury, joint effusion, tendinopathy, tendinitis, bursitis, and so on (Fig. 2). Through this study, they believe that although the robot-assisted teleultrasound has shortcomings in displaying deeper tissue of the limb and the flexibility of the robotic arm, it can still be used as a timely and effective means for diagnosing limb musculoskeletal and soft tissue injuries in the case of a lack of professional sonographers in grassroots units or extreme environments and provide imaging-based early clinical treatment.
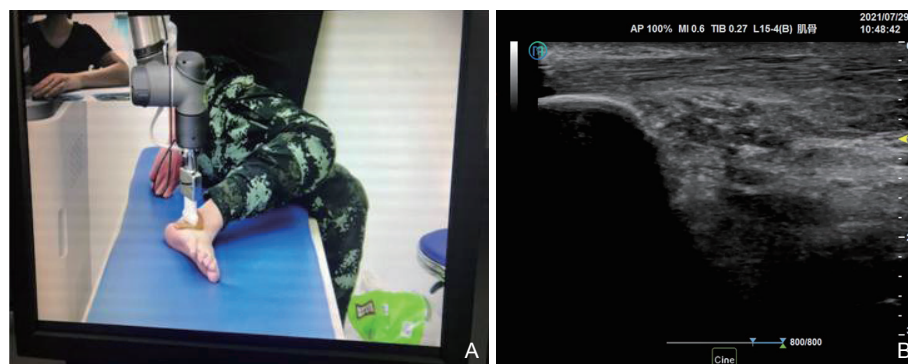
Figure 2 Application of robot-assisted teleultrasound in limb and soft tissue. (A) Robot-assisted teleultrasound in limb of scanning terminal in patients of a ministry; (B) Robot-assisted teleultrasound images of the limb in patients of a ministry.

The application of robot-assisted teleultrasound in other parts of the disease

In 2021, our team conducted robot-assisted teleultrasound examinations of mammary glands, peripheral blood, and gynecology on "Sanya-Yongxing Island" using the robot-assisted teleultrasound. We successfully performed an obstetric emergency examination on a case of sudden vaginal bleeding at 12 weeks of pregnancy, and timely treatment ensured the safety of both the mother and child. Additionally, we completed breast cancer screenings for 1,292 cases in "Beijing-Xizang Ali" with satisfactory results.

Clinical Application Value and Limitations of Robot-assisted Teleultrasound

Clinical application value

The traditional teleultrasound is like a pair of "clairvoyant eyes". The ultrasound consultant can view ultrasound images of difficult cases in remote areas or under special circumstances. In contrast, the robot-assisted teleultrasound adds a pair of "thousand-mile hands" for the ultrasonic experts. They can operate the robotic arm probe to obtain real-time ultrasound images, including instrument adjustment, parameter setting, patient coordination, and pressure angle and strength, allowing patients to access high-quality medical resources from superior hospitals without leaving their homes. This approach can alleviate the plight of the lack of sonographers in remote areas, primary medical units, and special environments. Through remote ultrasonic robot consultation, clear diagnoses can be made in the early stages of a disease, guiding timely treatment, realizing hierarchical diagnosis and treatment, avoiding delays in disease diagnosis, and unnecessary evacuation and transport, and reducing medical costs to a certain extent.

Limitations

In clinical practice, the robot-assisted teleultrasound still has some limitations. Firstly, it heavily relies on a stable, reliable, and efficient network operating environment, and cannot be used in special and remote areas without network coverage. Secondly, while the current 6-axis free-arm ultrasonic robot has been able to conduct clinical screening and diagnosis of cardiopulmonary, abdominal, and limb musculoskeletal and soft tissue emergencies, accurate examination of certain body parts and providing a good patient experience is still challenging due to limitations in force position perception and flexibility control. This restricts the capabilities of remote ultrasound as compared to traditional ultrasound.

Prospect of Clinical Application of Robot-assisted Teleultrasound

In the past 5 years, Chinese robot-assisted teleultrasound has rapidly become a leader in the field of medical robot application worldwide, from the approval of national medical device certificates to its rapid clinical application. Its development timeline is shorter than that of the Da Vinci surgical robot. While the Da Vinci surgical robot has a wider range of application scenarios and can be used to treat a variety of diseases, the robot-assisted teleultrasound is not an "alternative" but rather an indispensable tool, and has a larger future development space.

Application scenarios

The robot-assisted teleultrasound enables ultrasound to be carried out wherever people can go. Its application in remote areas, primary medical units, and isolation wards for COVID-19 infection has proven its feasibility in disaster relief, pre-hospital treatment, and large-scale emergencies.

The construction of the platform of the Internet of Things

Nowadays, with the emergence and popularization of 5G technology and cloud technology, issues such as network latency, storage, and information sharing difficulties have been solved. Based on the IOT (Internet Of Things), we can complete information sharing, resource scheduling and real-time joint consultation of multiple regions and disciplines. And the team of Wisonic Medical has developed a unique reverse control technology. Experts can remotely adjust the image parameters of ultrasound or perform measurements and other applications to improve consultation efficiency (Fig. 3). Combined with artificial intelligence and virtual reality technology to built the remote teaching platform, which could realize the scene reproduction teaching and interactive practical teaching. This can realize the sinking of high-quality teaching resources and help the construction and development of medical and health standards in remote areas.

Ultrasound interventional therapy

With the continuous improvement of flexible control and precision positioning technology of robot-assisted teleultrasound, the addition of a puncture intervention module in the operating system enables the robot to automatically navigate and locate the target, thereby achieving remote ultrasonic diagnosis and timely ultrasound interventional diagnosis.

Intracavitary robot-assisted teleultrasound

Taking transesophageal ultrasound as an example,

the application of intelligent robot's precise perception, force position compliance control, and intelligent image recognition technology can overcome the experience dependence of human operation and the limitations of human eyes on image recognition through man-machine collaboration [30].
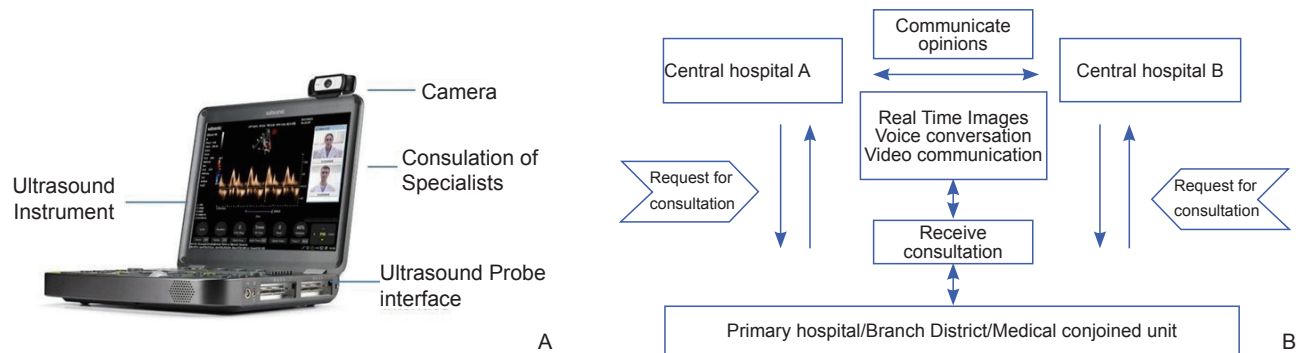

Figure 3 The teleultrasound of Wisonic Medical. (A) The prototype and main components; (B) Work principles.

Autonomous ultrasonic robot

With the rapid development and integration of artificial intelligence and robot technology, autonomy is the development direction of ultrasonic robots. Chinese company Wuhan Cobot Technology Co., Ltd has launched a prototype of an autonomous ultrasonic robot and is preparing for medical device registration. The robot includes six-axis collaborative robotic arm, six-dimensional force sensor, portable color doppler ultrasound instrument and other main components (Fig. 4A). Based on robot imitation learning technology, the ultrasound doctor's scanning technique is transformed into the basic program of robot scanning. Based on deep learning semantic segmentation, the position and imaging quality of each structure on the ultrasound video can be obtained in real time, and the contact force and moment data between the probe and the human body can be obtained based on the six-dimensional force sensor, and visual and force feedback can be integrated to guide the robot to adaptively adjust the posture and pressure of end effector to ensure the safety and effectiveness of ultrasonography (Fig. 4B). Autonomous ultrasonic robots can greatly reduce the dependence on the experience of ultrasound doctors, improve the consistency of ultrasound scans and diagnoses, and promote the digitization of ultrasound medical technology, especially for countries and regions that lack ultrasound doctors.
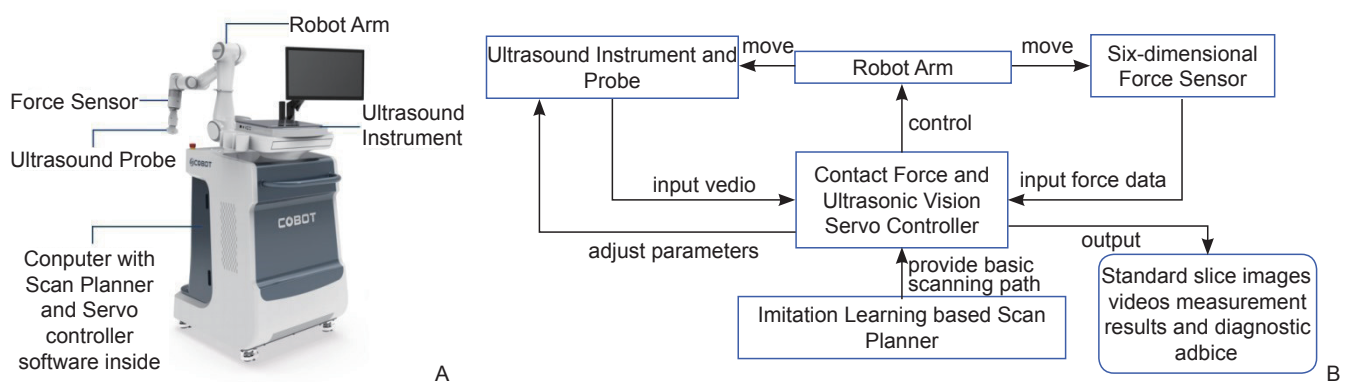
Figure 4 Autonomous ultrasonic robot. (A) The prototype and main components; (B) Work principles.

Acknowledgment

Conflict of Interest

The authors have no conflict of interest to declare.

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