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Diagnostic ultrasound probes: a typology and overview of technologies

Abstract: The routine clinical use of diagnostic ultrasound (US) has spread considerably worldwide in recent decades. This is due in large part to the availability of US probes that enable a wide range of clinical applications as well as provide performance benefits arising from technological improvements. This paper describes the current commercially available US probe types, lists some of their clinical applications and briefly explains the technologies that are responsible for recent enhancements in image quality and ergonomics. Our intention is to summarize information that will allow healthcare professionals to select the appropriate probe for the intended use and the desired performance-price ratio.

Keywords: Medical imaging, ultrasound probes, typology, technologies

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1 Introduction

Being free of ionizing radiation, sufficiently hazardless, portable, compact, cost-effective and real time, diagnostic ultrasound (US) is the most widely used cross-sectional imaging modality worldwide [1]. In addition to its ability to provide images of internal body anatomy, detect the dynamic movement of organs and reveal details of blood flow in real time [2], it offers a variety of imaging approaches, each providing a different type of clinically relevant information. These techniques include contrast enhanced ultrasound and elastography [1]. Diagnostic US imaging is used for many parts of the body [3], on fetal, neonatal, pediatric, adult, human and animal patients, and by users who may be for example sonographers, physicians, radiologists, surgeons, anaesthetists, midwives, paramedics or veterinarians. US imaging systems undergo rapid technology advancements and this results in a quick rotation of products available on the Market and change of price-performance ratio. Within this complex context, US probes play a crucial role in terms of both image quality and ergonomics. US probes are specialized to each clinical application and are becoming more and more sophisticated due to important technology improvements leading to more significant and consistent diagnostic information, faster and easier scanning and increased reliability. This paper presents an overview of US probes available nowadays on the Market, giving insights into different types and latest inner technologies. This analysis should help users and other stakeholders with purchasing and maintenance commitments to select the appropriate probe according to their clinical and economical needs. The description of both current categories and advanced performance arising from latest innovations allows an understanding of what contributes to different prices, features, quality level and breadth of applications.

2 US probes technologies

The US probe is responsible for conveying acoustic energy from the US system into the body. The choices for design, materials and manufacturing technologies play a key role in achieving high image quality. Traditionally, the probe consists in an acoustic stack composed of a backing block, a piezoelectric ceramic layer, acoustic matching layers and a lens [2]. The piezoelectric layer is a critical component because it is the active material that converts the electrical signal to an US wave and vice versa [4]. In the last decades, lead zirconate titanate (PZT) ceramic was the predominant solution due to its excellent piezoelectric properties, chemical inertness, physical strength, and easy and inexpensive

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manufacturing [5]. However, PZT has some serious drawbacks as the very high acoustic impedance (20 times higher than human tissue) and power loss from low conversion efficient [6], that have motivated the investigation of a new generation of piezoelectric materials, such as single crystal lead magnesium niobate-lead titanate (PMN-PT) and lead zinc niobate-lead titanate (PZN-PT). Grown in a monocrystalline form with an increased efficiency of poling, single crystals exhibit an electromechanical coupling factor (k_{33}) and a piezoelectric coefficient (d_{33}) up to 90% and three times higher than PZT, respectively. Compared with PZT, this technology allows the development of US transducers with larger bandwidth, enhanced sensitivity and lower losses. As a result, penetration and image resolution are improved, providing more detailed diagnostic information even for difficult-to-image patients [4]. A further increase in efficiency of signal transmission is obtained using multi-layered crystal technology, an advanced architecture developed to accomplish an enhanced image quality. The core of this technology is a piezoelectric chip composed of several layers [7], which are mounted in the acoustic stack to improve electrical matching with the cable and reduce the energy and sensitivity loss due to the typical mismatch between the output impedance of transducer and load impedance of cable.

Micromachined ultrasound transducers (MUTs), namely capacitive MUTs (cMUTs) and piezoelectric MUTs (pMUTs), are practical substitutes of piezoelectric bulk ceramics for the design of transducers. cMUTs consists of micromachined surface membranes on silicon substrates [8], which exploit the electrostatic transduction to transmit and receive acoustic energy [9], [10], whereas pMUTs work by taking advantage of the flexural motion of a thin membrane driven by a thin piezoelectric film [11], [12]. Of the two technologies, cMUTs are already integrated in commercial products, providing high spatial resolution from wide bandwidth (excess of 100%) and narrow beam width due to easier manufacturability of multiple rows of elements [10].

Innovation on piezoelectric materials alone is not enough for augmenting image quality. A significant contribution to the performance of modern probes derives from the application of multiple adaptive matching layers (MAMLs) [6] and the acoustic amplifier (AA) [13]. Both methods can be thought of as working by tuning the acoustic impedance of the transducing element, transmitting a more faithful replica of the intended pulse, attaining an even wider bandwidth and higher sensitivity. MAMLs, mounted between the element and the body, consist of a thin multi-layer with a tapered acoustic impedance across the layers [6], whereas AAs, sandwiched between the backing block and the element, detect the energy transmitted backwards by the element and retransmit it in-phase, forwards. This reuse of acoustic energy that would otherwise be dispersed makes for less heat dissipation. This is a crucial point since the heat dissipated in the transducer often degrades the performance of the device, especially sensitivity and penetration.

Several options are available to implement the thermal management. An example of an efficient cooling system is that based on a heat transfer device made of a graphene-based material, either pure graphene or a graphene-loaded resin, which is placed on the front of the transducer assembly to work also as part of the matching layer into the body [14]. Alternatively, a cooling system embedded at the rear of the transducer between the backing block and the acoustic amplifier is also achievable. It is composed of a heat spreader, which transfers heat away from the heat source, and a heat sink, which dissipates the heat [15].

Conventional 1D transducer arrays have good lateral and axial resolution, but elevation resolution is limited by the fixed-focus lens determining the image slice profile. Multi-row (typically 3-8 rows) transducer arrays can provide a thin image slice over an extended depth of field, providing improved spatial and contrast resolution. There are two implementation strategies [16]: i) 1.5D arrays that have electronic beamforming in both azimuth and elevation, allowing dynamic control of the elevation aperture and focus, and ii) 1.25D arrays that have the elevation rows connected together by switches allowing static elevation focusing determined by a mechanical lens with a fixed focus (or foci). 2D matrix arrays, consisting of many thousands of transducer elements, enable full electronic elevation apodization, focusing and steering, and providing volumetric imaging in real time. 1.25D, 1.5D and 2D transducers are in commercial production, optimized for different clinical applications.

3 US probes typology

US probes are available in a wide range of sizes, shapes, frequencies, with each probe optimized to specific clinical imaging applications and resulting image formats. Proper choice of probe before scanning is crucial and depends on several factors such as exam type, scan depth and patient characteristics. Probes may be classified in two main categories: conventional probes (linear, phased and convex arrays) and speciality probes that are dedicated to specific clinical applications (for instance, intraoperative and trans-esophageal probes).

3.1 Conventional probes

The most prevalent US probe types are linear, phased and convex arrays (Figure 1). Linear Arrays (LAs) are flat and provide rectangular or trapezoidal image format with a field of view that is roughly equal to the probe length [16]. They operate over many frequency ranges, the choice of which depends on the tissue depth of interest (the higher the frequency, the better the resolution, but the poorer the depth of tissue penetration). Typical frequency ranges for available probes are: medium (3-11 MHz) for vascular and small parts [16], high (4-18 MHz) for vascular and musculoskeletal, and very high (8-24 MHz) for superficial anatomy (e.g., dermatology, rheumatology, superficial musculoskeletal). Ultra-high frequency (30-70 MHz) linear arrays also exist for dermatology and pre-clinical research. Phased arrays (PAs) are also flat, but have smaller footprint to fit between ribs, being primarily used for cardiac imaging. To achieve a field of view sufficient to image the entire heart, they operate at different frequencies depending on patient: 4-12 MHz for neonatal, 2-12 MHz for pediatric, 1-5 MHz for adult [16]. Convex arrays (CAs) (1-9 MHz) are curved, with a radius of curvature (ROC) in the range 40-60 mm, and are used for abdominal and obstetrics applications [16].

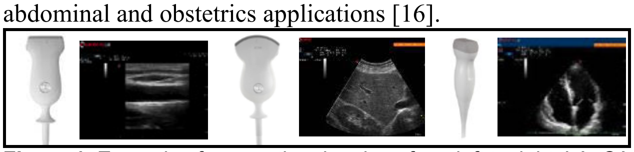

Figure 1: Example of conventional probes: from left to right, LA, CA and PA and the relative image format.

CAs with smaller ROC (13-20 mm), namely micro-convex (MC) arrays, typically operate in the frequency range 3-11 MHz and are for pediatrics, vascular and veterinary uses. MCs specially designed for interventional use, mainly liver biopsy, have lower frequency (2-7 MHz). Endo-cavity (EC) probes are also curved (in general, ROC is 10 mm) and are designed to access specific acoustic windows in the body (as in obstetrics and gynecology). More complex, are bi-plane transrectal probes that have dual arrays: linear + convex (4-13 MHz/3-13 MHz) or convex + convex (2-12 MHz/2-12 MHz). (Figure 2)

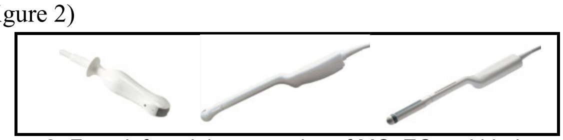

Figure 2: From left to right, examples of MC, EC and bi-plane transrectal probes

3.2 Speciality probes

A list of speciality US probes available on the Market, with a description of some their peculiarities, is provided [2], [3]:

- Adult and pediatric trans-esophageal (TEE): imaging of the heart made from within the esophagus.
- TEE for continuous patient monitoring: hemodynamic US for use in the intensive care unit (ICU).
- Transnasal micro-multiplane TEE.
- Intraoperative: imaging during a surgical procedure.
- Intraoperative bi-plane: simultaneous biplane imaging with two orthogonal planes for needle guidance.
- Interventional CA and LA with biopsy guidance: imaging with direct biopsy access within the array width.
- Hockey stick: mainly dedicated to musculoskeletal imaging.
- Hockey stick with motorized tip for intraoperative procedures.
- Laparoscopic: imaging to guide and evaluate laparoscopic surgery.
- LA array manoeuvred by robotic surgery arm.
- Electro-mechanical 3D (LA, CA, EC, MC, LA with parallel acquisition) for 4D real-time Imaging.
- Intravascular (IVUS): imaging of the interior of arteries from catheter-tip transducers inserted in them.
- Intracardiac: imaging from within the heart.
- 3D matrix (LA, CA, PA, TEE).
- 3D Electro-mechanical transrectal: anorectal 3D Imaging with 360° image field.
- Prostate triplane: images in three planes (transverse, sagittal, end-fire), plus 3D image reconstruction.
- Dual-headed probe integrating both LA and PA that is typically used at point of care (POC).
- Oral probe: intra-oral imaging.
- Trans-urethral probe.
- Endoscopic US probe: a small transducer is installed on the tip of an endoscope with a camera. It is used to image the digestive tract and the surrounding organs.
- PA, LA and CA with USB connection
- PA, LA, CA wireless probes.
- Pencil Doppler: non-imaging CW and PW Doppler.
- Photoacoustic probes: allowing tissue-illumination for US generation by optical-tissue interactions.
- Automated breast ultrasound volume scanner (ABVS) with linear automatic scanning array.
- 3D whole breast US tomography system incorporating a circular US transducer immersed in water for prone patient acquisition.

Figure 3 shows some examples of speciality probes.

3.3 Additional features

The user interface ergonomics of the US systems and probes is of primary importance due to the increased use of US systems in the everyday clinical practice especially for problems as work-related musculoskeletal disorders (WRMSD) for sonographers [3]. The percentage of sonographers reporting consequences of pain and discomfort is close to 80% within the first five years of entering the profession. A new probe design concept has been developed in recent years in order to reduce scanning fatigue and related WRMSD. Transducers with a dual-possibility hand grip (appleprobe™ design) are available (pinch grip and palmar grip) in order to provide a neutral wrist position, reduced fatigue and making probes easier to handle [17]. An important aspect of probe typology and ergonomics is represented by biopsy kits which are available for different uses and body areas, and for guidance of fine needle aspiration (FNA), percutaneous interventions and core biopsies. Another accessory that can be attached to an US probe is support for navigation systems (usually electromagnetic or optical) for real-time fusion imaging. A single electromagnetic or optical sensor, secured through a highly ergonomic mounting bracket on the probe, enables sufficient spatial accuracy and precision and ensures a comfortable workflow which does not need probe grip changes and/or major probe weight changes [3]. When cleanability and sterility are big issues, probe or even whole system sterile covers can be used. US systems are used in different clinical environments and each US examination involves contact between the probe and patient's skin, mucous membrane or sterile tissues. Appropriate cleaning, disinfection or sterilization is required according to the risk of pathogen transmission and subsequent infection associated with the US procedure. Depending on the level of this risk, US probes are classified as non-critical, semi-critical or critical. Users must adequately clean and reprocess the transducer to ensure infection prevention [18].

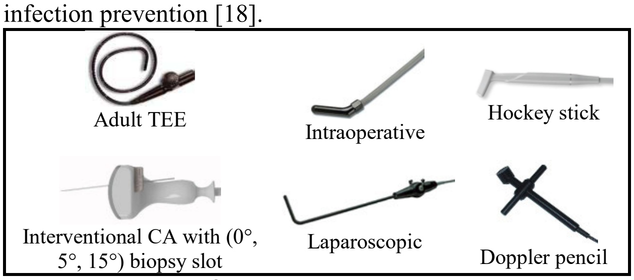

Figure 3: Examples of speciality probes

3.4 Conclusion

The full range of modern US probe types and inner technologies has been described for purposes of supporting biomedical engineers, physicians, sonographers and healthcare stakeholders involved in purchasing decisions and maintenance, hopefully increasing their level of knowledge for choosing a product that has the most appropriate technical-clinical performance/price ratio.

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