Advances In Ultrasound Transducer Technologies for Portable Medical Imaging: A Comparative Review of Piezoelectric, CMUT, And Optical Approaches

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Abstract. Ultrasonic imaging is a cornerstone of modern medical diagnostics. Although Piezoelectric Materials Ultrasound Transducers (PMUT) are well-established, their performance limitations—particularly in sensitivity and adaptability—become apparent as medical devices trend towards miniaturization and portability. In response, emerging technologies such as Capacitive Micromachined Ultrasonic Transducers (CMUT) and optical ultrasound transducers have emerged as promising alternatives. Optical ultrasound transduction, in particular, combines the high contrast of optical imaging with the deep penetration of ultrasound, representing a significant direction for future development. This review systematically compares three principal types of medical ultrasound probes: piezoelectric, CMUT, and optical. It elaborates on their fundamental operating principles, internal architectures, and respective advantages. A comparative analysis is presented to evaluate their performance, leading to a discussion on the future trajectory of ultrasound probe technology, with a specific focus on their integration into wearable and handheld devices. The ultimate goal of this review is to bridge the gap between novel transducer principles and practical clinical application, thereby contributing to the advancement of a new generation of portable diagnostic imaging.

Keywords: Ultrasound transducer; piezoelectric transducer; Capacitive Micromachined Ultrasonic Transducer (CMUT); Optical ultrasound probe; Handheld ultrasound device (HHUD).

1. Introduction

Ultrasonic imaging technology is currently one of the predominant medical imaging techniques. It offers advantages such as being non-invasive and highly efficient [1], and it enables real-time imaging, thereby providing significant assistance to doctors in precisely identifying the locations of lesions. According to statistics from 2019, the annual number of ultrasound examinations reached approximately 2 billion, far surpassing approximately 200 million CT examinations conducted each year. This trend has continued to the present and is expected to persist in the future.

Ultrasound imaging is a widely used technique for visualizing soft tissues, such as in prostate and breast examinations, offering real-time, high-resolution imaging without ionizing radiation. Its non-invasive and radiation-free nature distinguishes it from modalities like X-ray, CT, MRI, OCT, and nuclear imaging, making it one of the most prevalent diagnostic tools. The ultrasound transducer is the core component of an ultrasound imaging system, commonly known as the ultrasound probe. Its primary function is to achieve the interconversion between electrical energy and ultrasonic energy (a form of mechanical energy). This generally includes the transmission of signals (converting electricity into ultrasound) for detection and the acquisition of signals (converting ultrasound back into electricity). Medical ultrasound transducers are primarily classified by their physical principles for converting acoustic energy into electrical signals. While traditional piezoelectric transducers operate based on the piezoelectric effect, emerging transducer types show considerable potential. For instance, the inception of CMUT technology for Intravascular Ultrasound (IVUS) dates to 2002 and in 2006 laser-diode-based photoacoustic imaging (PAI) was used in visualizing blood vessels, which is one of the most significant findings in ultrasound. Furthermore, Westphal et al using PVDF-TrFE to create probes that activate automatically upon skin contact making medical imaging devices more portable [2].

The development of advanced ultrasound technologies, such as CMUTs and optical probes, has significantly broadened the scope of clinical applications. These now encompass a wide range of diagnostic procedures, including echocardiography, breast imaging, abdominal scans, transrectal exams, intravascular imaging, and prenatal diagnostics. In addition to advancements in imaging technology and application scenarios, in recent years ultrasound systems have evolved toward portability and wearability, giving rise to handheld ultrasound devices (HHUDs). Compared to traditional point-of-care ultrasound (POCUS), these devices offer advantages such as portability, low cost, energy efficiency, and operational flexibility [3]. Particularly in resource-limited regions—including countries such as Ghana, India, Zambia, and Kenya—portable ultrasound has been widely embraced as a practical tool for patient screening. Nonetheless, challenges remain, including limited image resolution, which continues to motivate research into improving sensitivity and integration for next-generation devices. While current researchers primarily improve imaging quality by continuously upgrading equipment and introducing AI for image processing, this paper centers on the developments in device advancement.

This review systematically compares these transducer types—piezoelectric, CMUT, and optical—in terms of their operational principles, acoustic performance, scalability, and suitability for integration into future handheld or wearable ultrasound devices. The discussion also extends to novel materials and flexible transducer designs, which may further enable conformal and patient-specific imaging applications. Ultimately, the evolution of ultrasound technology will likely hinge on leveraging the complementary strengths of these transducer classes to achieve devices that are not only more compact and affordable, but also capable of higher resolution and multimodal imaging.

2. Structure and Working Principle

2.1. Piezoelectric Ultrasound Probe

Piezoelectric materials are characterized by their fast response, high speed and precision, making them widely utilized in sensing devices. The materials contain natural and synthetic materials. Quartz, topaz, Rochelle and even wood, bone are natural piezoelectric materials. Besides, synthetic piezoelectric materials include ceramics and crystals such as barium titanate ($BaTiO_3$), lead zirconate titanate ($PbZr_xTi_{1-x}O_3$), lithium niobate ($LiNbO_3$), and potassium niobate ($KNNbO_3$), as well as polymers and composite materials like polyvinylidene fluoride (PVDF). Among these, PVDF-TrFE has emerged as a high-performance flexible material and is now extensively used in the development of wearable devices. Ultrasound transducer contains several layers as presented in Figure 1. In a typical ultrasound transducer, the acoustic lens is situated at the foremost part of the assembly, commonly fabricated from materials such as silicone rubber. Its primary role is to focus on the ultrasonic beam, thereby enhancing the lateral resolution of the resulting image. Positioned between the piezoelectric layer and the acoustic lens or human tissue, the matching layer serves a critical function in mitigating the substantial acoustic impedance mismatch between the high-impedance piezoelectric material and the low-impedance soft tissue. By employing materials engineered to specific acoustic impedance values—often designed to a quarter-wavelength thickness—this layer significantly reduces wave reflection at the interface, leading to improved transmission efficiency of acoustic energy and a broader operational bandwidth. At the rear of the piezoelectric element, the backing material is applied to dampen and absorb residual vibrations that propagate backward. This damping effect shortens the acoustic pulse duration and minimizes ringing, thereby improving the axial resolution of the image, though generally at the expense of some sensitivity. In addition, the most critical component is the piezoelectric layer, which is the signal generation and reception element fabricated from piezoelectric materials, which can produce the piezoelectric effect.

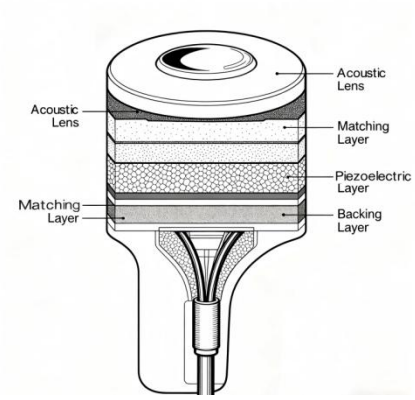

Fig. 1 Structure of Piezoelectric Ultrasound Probe (Picture credit: Original)

2.1.1 Development of piezoelectric materials

Piezoelectric materials are substances that exhibit the piezoelectric effect. When giving mechanical stress, these materials undergo charge displacement, resulting in a change in the overall electric dipole moment and generating an electrical signal. Conversely, when giving an electric field, the material experiences mechanical deformation. Initially, piezoelectric ceramics were primarily used, with $BaTiO_3$ being the first material discovered to exhibit an exceptionally high dielectric constant (up to 1100). Early scientists focused on investigating its applications in sonar and ultrasonic therapy. In last century, the development of lead zirconate titanate (PZT) ceramics marked a historic milestone in piezoelectric research. PZT has since become extensively developed and widely used piezoelectric materials to date. Following the earlier pioneering work in the 2010s, such as Ghaffari et al.'s 2014 demonstration of PZT nanoribbons on flexible substrates for biomechanical energy harvesting, which paved the way for compliant piezoelectric devices [4]. Kim et al.'s 2011 development of epidermal electronics with stretchable interconnects that provided a crucial architectural blueprint [5]. In 2018, Wang et al. developed a conformable PZT composite array for gel-free, continuous blood pressure monitoring [6], while in 2020, Pashaei et al. created a flexible dual-array PZT transducer for simultaneous nerve imaging and ultrasonic modulation [7]. Today, the sol-gel method has garnered significant attention from both academia and industry due to its ease of processing, high homogeneity, flexibility, consistency, and low cost. Savoia et al. proposed a PZT PMUT 64×184 1-D array designed for ultrasonic carotid imaging, which was tested on live human patients [8]; Sadeghpour et al. developed a 128-element PZT PMUT array for medical ultrasound imaging and conducted testing in an underwater environment [9]. This technique enables the facile large-scale production of PZT thin films.

2.1.2 Strengths, weaknesses and future development of PMUT

PZT materials are widely used in the manufacturing of piezoelectric ultrasound transducers and ultrasound therapy applications due to their high dielectric constant and mature fabrication processes. However, in recent years, concerns have been raised regarding PZT materials. Due to inherent concerns regarding the potential environmental and human health issues associated with lead-based piezoelectric materials, research on lead-free alternatives has grown rapidly these years. Piezoelectric ultrasound transducers, despite their numerous advantages, are limited by the environmental and health concerns associated with lead-based materials. Currently, four major types of lead-free piezoelectric materials have been extensively utilized in such devices, including (K, Na)NbO_3(KNN)-based, $BaTiO_3$(BT)-based, $BiFeO_3$(BF)-based, and (Bi, Na)TiO_3 (BNT)-based ceramics and thin films [10]. Among these, ceramics in the bismuth ferrate (BF) system exhibit superior properties and their high Curie temperature qualifies them as promising candidates for use in high-temperature environments. To further enhance device performance, future research should focus on two key directions: On one hand, it is essential to improve the bandwidth and sensitivity of transducer arrays through optimized selection of piezoelectric materials, advances in micromachining technology, and structural design improvements, along with the development of high-performance lead-free

alternatives. On the other hand, the fabrication remains challenging, stemming mainly from the challenges associated with reliable deposition of high-performance thin films.

2.2. Capacitive Micromachined Ultrasound Transducer

CMUT represents another promising type of ultrasound transducer technology. Compared to PMUT, CMUT enhanced electromechanical coupling, improved receiving sensitivity, and an extended bandwidth, demonstrating overall better performance and their conventional counterparts. Furthermore, this type of transducers is widely used across various fields such as electronics, energy, environmental protection, and biomedical applications due to their high surface area, enhanced electronic properties, excellent biocompatibility, and ease of miniaturization and integration [11]. Capacitive ultrasonic transducers can function as both transmitters and receivers of ultrasound. In transmission mode, an AC voltage alters the electric field between the electrodes, causing the membrane to vibrate and thereby converting electrical energy into mechanical energy. In reception mode, externally applied mechanical energy or incoming ultrasonic waves induce vibration in the membrane, resulting in a change in capacitance and converting mechanical energy back into electrical energy. This process operates on a similar underlying principle as that of acoustic speakers.

2.2.1 Structure and fabrication of CMUT

CMUT is a type of electrostatic transducer. They are typically composed of a top metallization, a vibrating membrane, a supporting rim, a hermetically-sealed cavity, a dielectric film, and a base wafer. For CMUT with circular plates, the mechanical component is modeled by characterizing the vibrational behavior of the membrane. The key parameters governing membrane vibration are mass, stiffness, and damping. The membrane's equation of motion is governed by Newton's second law:

$$w(r) - \frac{p_0 a^4}{64D}\left(1 - \frac{r^2}{a^2}\right)^2 = w_{pk}\left(1 - \frac{r^2}{a^2}\right)^2. \quad (1)$$

w here denotes the deflection of the plate as a function of the radial position, is the radius of the plate, represents the flexural rigidity of the plate material, and corresponds to the maximum plate deflection.

The history of CMUT fabrication processes began in the 1990s. In 1994, Haller and Khuri-Yakub pioneered the successful fabrication of CMUTs using surface micromachining technology. They employed low-pressure chemical vapor deposition (LPCVD) silicon nitride as the structural layer and thermal oxide as the sacrificial layer, with the membrane released via wet etching [12]. This established the fundamental paradigm for CMUT manufacturing, though the process faced challenges such as cavity contamination and membrane stiction.

Subsequently, researchers pioneered novel fabrication strategies to resolve the critical issue of cavity sealing in CMUT. They used electron beam lithography to create submicron holes, which were then vacuum sealed via conformal LPCVD silicon nitride deposition, effectively preventing moisture and particulate contaminants from entering the cavity. To improve process control, a pre-patterned sacrificial layer was introduced. This method uses amorphous silicon, which has a high etch selectivity to silicon nitride. Etch holes were placed around the membrane and sealed with low-temperature oxide (LTO). This allowed for precise control of the cavity dimensions and eliminated the need for timed etching.

Entering the 21st century, the focus shifted toward integration and performance optimization of CMUT. Huang et al. developed a revolutionary wafer bonding process that utilized silicon-on-insulator (SOI) wafers bonded in vacuum to a backplate wafer with pre-formed cavities [13]. This resulted in perforation-free, single-crystal silicon membranes with uniform thickness and minimal stress, significantly improving device consistency and performance. Meanwhile, to enable monolithic integration of CMUTs with readout circuits, Memmi et al. developed a low-temperature CMOS-compatible process using plasma-enhanced chemical vapor deposition (PECVD) silicon nitride as the structural layer and polyimide as the sacrificial layer, reducing the maximum process temperature to below 400°C [14]. In recent years, process exploration has expanded to new material systems.

Hutchins et al. utilized microstereolithography (MSL) to rapidly prototype polymer-based CMUT, offering a new technical pathway for low-cost applications such as structural health monitoring [15]. Omidvar et al. operates at frequencies up to 15 MHz CMUT and is designed for musculoskeletal imaging [16]. Pang et al. developed a fully transparent and flexible CMUT using roll-lamination technology to fabricate SU-8 membranes and ITO electrodes, making it suitable for integration into display panels and optical-compatible applications [17]. Joshi et al. proposed the use of ICP-CVD silicon nitride as the structural layer combined with laser lift-off technology to release the polyimide substrate [18], achieving high-performance and high-yield flexible CMUT manufacturing, along with the development of an automated testing method.

Throughout its evolution, CMUT fabrication has advanced from early high-temperature surface micromachining to wafer bonding, low-temperature CMOS-compatible processes, 3D integration, and novel polymer-based manufacturing. Each innovation has addressed critical technical bottlenecks of the previous stages, enabling CMUT to transition from laboratory devices to broad industrial and medical applications.

2.2.2 Strengths, weaknesses and future development of CMUT

Compared to PMUT, CMUT exhibits exceptional bandwidth, making them suitable for high-resolution imaging and harmonic imaging. According to research by Salim, CMUT can easily achieve a fractional bandwidth of up to 123% in immersion applications [11], showing great potential in intracavitary imaging such as IVUS and underwater imaging, while also avoiding the lead-related issues associated with PZT materials. However, several challenges remain. Firstly, imaging performance is significantly affected by the material's capacitance, resulting in lower signal-to-noise ratio (SNR) in images. CMUT also requires higher operating voltages. In Joshi's study, PMUT typically operates between 5V and 80V, whereas CMUT demands a high DC bias voltage (40V ~ 120V) in addition to an AC excitation voltage [18], leading to complex operation and an increased risk of breakdown. Furthermore, achieving flexibility for wearable device integration remains a major challenge due to the inherent rigidity of conventional capacitive materials. Joshi noted that both the number and design strategies of flexible PMUT far exceed those of CMUTs. PMUTs can be directly fabricated on flexible substrates such as polyimide (PI), while CMUT often relies on complex hybrid methods (e.g., silicon islands connected with PDMS) or polymer-based approaches, which often come with performance trade-offs.

2.3. Optical Ultrasound Transducer

2.3.1 Photoacoustic imaging

Photoacoustic Imaging (PAI), is a novel bioimaging technique combining optical contrast with the deep penetration capability of ultrasound, has seen its development closely linked to innovations in ultrasound detection technology. Its fundamental principle is based on the photoacoustic effect: when biological tissue absorbs pulsed laser energy, thermoelastic expansion occurs, generating ultrasonic waves, which is presented in Figure 2. Since ultrasonic waves experience significantly less scattering than light waves in biological tissues, this enables deeper penetration for imaging. By detecting these photoinduced ultrasonic signals and applying reconstruction algorithms, photoacoustic imaging can provide high-resolution, high-contrast structural images of biological tissues. Furthermore, leveraging multi-wavelength excitation and computational analysis, this technique can also extract functional information such as hemoglobin concentration and blood oxygen saturation, demonstrating considerable potential in various biomedical fields including oncology, cardiovascular diseases, and ophthalmology [19-21].

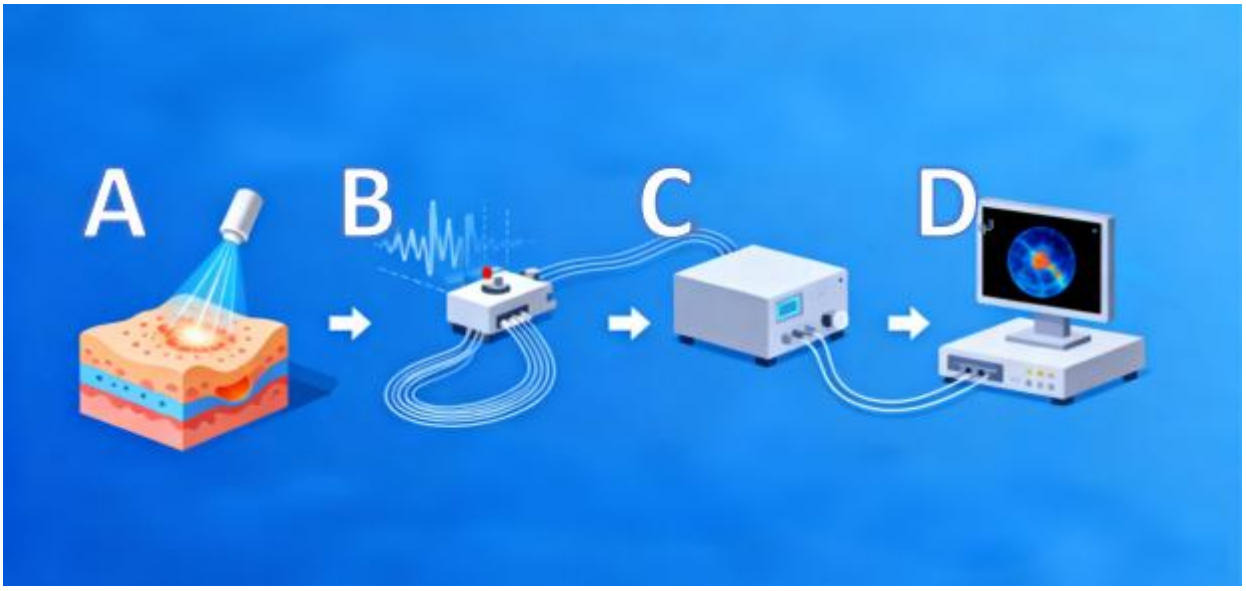

Fig. 2 Photoacoustic Imaging Workflow and Signal Processing; A: Ultrasound Generation: A pulsed laser illuminates the tissue via the probe; B: Signal Capture: The propagating photoacoustic signals are captured by a Fabry-Pérot (FP) interferometer sensor. A continuous-wave interrogation laser detects the ultrasonic-induced changes in the sensor; C: Signal Transmission: The modulated light signal, which carries the ultrasonic information, is transmitted back to the computer; D: Image Reconstruction: The main unit processes the received signals. Using reconstruction algorithms, it generates a high-resolution image that maps the optical absorption distribution within the tissue (Picture credit: Original).

Optical ultrasound sensors can be categorized into two types based on whether they operate on a resonance principle. The signal from resonant sensors originates from changes in the acoustic cavity induced by variations in acoustic pressure, resulting in detectable alterations in the intensity, phase, and wavelength of the interrogation light. Fabry-Pérot interferometers (FPI) and Bragg gratings are classic examples of resonant optical sensors [22]. Non-resonant sensors primarily employ free-space methods or photo elastic approaches, with the Michelson interferometer being the most classic example. Comparisons of PAI imaging performance mainly focus on frequency, sensitivity, and acceptance angle. The frequency of ultrasound sensing is crucial for image quality, as light-induced ultrasound waves possess a broad spectrum.

Currently, the most widely used sensors in PAI include FPI, fiber laser sensors, and π-phase-shifted fiber Bragg gratings (π-BG). In 2011, π-BG was first used for ultrasound detection, achieving a bandwidth of up to 10 MHz. Wissmeyer et al. employed π-BG in all-optical photoacoustic microscopy, this integration enabled optical-resolution photoacoustic microscopy [23]. Guggenheim et al. proposed a polymer-based plano-concave microresonator integrated based on the principle of FPI, enabling omnidirectional response and a 40 MHz bandwidth for high-resolution imaging of mouse ear vasculature and porcine aortas [24]. Ansari et al. developed a multi-core fiber F-P array, achieving forward-viewing endoscopic photoacoustic imaging with a resolution of 45–170 μm [25]. Shnaiderman et al. developed a silicon waveguide-etched detector (SWED) based on a Bragg grating, achieving a 230MHz bandwidth and a sensitivity of 9, with resolution approaching that of optical microscopy [26]. Hazan et al. further optimized this, achieving a sensitivity of 2.2 and a bandwidth of >200MHz for high-resolution photoacoustic tomography of mouse ear vasculature [27]. In recent years, Whispering Gallery Mode (WGM) microcavities have become a major research focus. Yang et al. utilized a Brillouin laser microsphere for multi-parameter sensing, including ultrasound [28]. Tang et al. achieved single-particle photoacoustic vibration spectroscopy for microbial cell identification [29].

2.4. The possibility of Integration into HHUDs

HHUDs have emerged as a future direction for ultrasound probe development. Although the current image resolution of HHUDs remains inferior to that of POCUs, numerous studies have demonstrated that this difference does not significantly impact surgical or clinical diagnosis [30]. Nevertheless, improving image quality remains necessary for HHUDs.

Several medical companies have already developed clinically viable handheld devices, such as Butterfly Network Inc.'s Butterfly iQ+, Clarius Mobile Health's Clarius, EchoNous' Kosmos, Mindray's TE Air, GE Healthcare's Vscan Air SL and CL, and Philips Healthcare's Lumify. Among these, the Butterfly iQ+ utilizes CMUT (Capacitive Micromachined Ultrasonic Transducers) technology, while the other five devices employ PMUT (Piezoelectric Micromachined Ultrasonic Transducers). All probes feature M-mode and color flow Doppler imaging modes, but only the Kosmos offers continuous-wave Doppler functionality.

The Butterfly iQ+ innovatively employs a CMUT chip that integrates multiple functions into a single unit. This probe covers multi-frequency applications across various scenarios and is more cost-effective (priced at only $3,500 or $2,700 + $420/year) compared to PMUT-based devices, which typically exceed $4,000.

For optical ultrasound probes, signal acquisition is still achieved through PMUT technology. However, miniaturizing optical systems remains a significant challenge. Although handheld devices have been developed, such as the one created by Liu et al., which integrates components into a relatively small system, their size remains substantially larger compared to handheld CMUT and PMUT devices [31]. Further research is needed, and advancements in silicon photonics technology may hold the key to developing portable optoacoustic imaging systems. Silicon photonics-based optoelectronic devices can enable efficient signal transmission with low loss and high speed, potentially making portable optoacoustic imaging technology feasible.

3. Conclusion

Based on the comparative analysis of the three major ultrasound transducer technologies—PMUT, CMUT, PAI, this review systematically evaluates their respective performance characteristics and integration potential. Among the advanced ultrasound transducer technologies, PMUT technology stands out due to its reliance on mature material systems and fabrication processes. It offers notable advantages such as low driving voltage, excellent power efficiency, and high portability, making it particularly suitable for integration into handheld devices. However, the use of lead-based materials in PMUTs raises significant environmental and biosafety concerns, and their performance is somewhat limited in high-frequency applications. In contrast, CMUT technology, which is manufactured using semiconductor processes, offers several performance benefits, including ultra-high image resolution and broader bandwidth. Additionally, CMUT has the advantage of being lead-free, addressing some of the environmental concerns associated with PMUT. Despite these benefits, CMUT requires high DC bias voltages for operation, and their traditionally rigid structures present challenges for flexible integration into wearable devices. Meanwhile, PAI technology distinguishes itself with its exceptional resolution and unique optical contrast capabilities, making it highly promising for functional imaging applications. However, the complexity of optical systems and their high energy consumption currently pose significant barriers to miniaturization and widespread clinical adoption, especially in portable scenarios. Yet, its system complexity, high energy consumption, and difficulties in miniaturization currently hinder its widespread clinical adoption, particularly in portable scenarios. Table 1 illustrates a comparison of the three types of probes in various aspects.

Table 1. Comparison of the advantages and disadvantages of three probes

	PMUT	CMUT	PAI
Manufacture	Mature Materials, Lead-Containing	Semiconductor Process, Safe	Optical Materials, Complex
Energy consumption	Low driving voltages, good power efficiency	High DC bias voltage (40V-120V)	Pulsed lasers are highly energy-intensive
Integrated	Easy Integration, Highly Portable	traditional structures are rigid	Difficult Integration, Low Portability
Image Resolution	High Resolution	Ultra-High Resolution	Ultra-High Resolution
Penetration Depth	Excellent Depth	Good Depth	More Excellent Depth

When receiving the paper, we assume that the corresponding authors grant us the copyright to use the paper for the book or journal in question. When receiving the paper, we assume that the corresponding authors grant us the copyright to use. Currently, several handheld ultrasound devices based on PMUT and CMUT technologies have been successfully introduced into clinical practice. While their image quality may not yet fully match that of large stationary systems, their portability and cost-effectiveness have already proven invaluable in point-of-care settings. It is worth noting that achieving portability in these devices often involves a trade-off with some image quality. Meanwhile, PAI systems remain far from achieving true portability due to the significant challenges in miniaturizing complex optical systems, despite their unparalleled imaging performance.

Future advancements in ultrasound probe technology will rely on interdisciplinary collaborations and innovations in materials science. A critical yet frequently overlooked challenge is the current dependence on coupling gel, which causes patient discomfort. The development of solid flexible coupling materials or coupling agent-free detection methods would substantially improve the patient's experience. Looking ahead, integrating the complementary strengths of piezoelectric, CMUT, and optical technologies will be crucial for creating next-generation diagnostic devices that deliver superior image quality, enhanced portability, reduced cost, and multimodal imaging capabilities. Promising research directions include multispectral imaging, real-time surgical navigation, multimodal system integration, and AI-enhanced functionality. These technological advances are expected to revolutionize clinical diagnostics, enable real-time interventional procedures, and ultimately elevate the standard of patient care.

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