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Development of a Low-Cost Portable Ultrasound Probe for Point-of-Care Cardiac Imaging

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ABSTRACT

Background: Cart-based echocardiography is the diagnostic reference standard but its cost, size, and sonographer dependence limit availability outside specialized settings. Objective: This narrative review synthesizes published literature on transducer technologies, commercial platforms, and clinical evidence underlying low-cost portable ultrasound probes for point-of-care cardiac imaging. Methods: Peer-reviewed studies and reviews on capacitive and piezoelectric micromachined ultrasonic transducers (CMUTs, PMUTs), smartphone-connected handheld devices, and diagnostic/cost-effectiveness evaluations were identified and synthesized. Findings: Wafer-scale CMUT- and PMUT-based arrays with single-chip beamforming electronics have enabled devices such as Butterfly iQ, Clarius, Lumify, and Vscan to approach stethoscope-level affordability while retaining useful image quality. Validation studies show good agreement with comprehensive echocardiography for chamber size, systolic function, and valvular disease, with reduced but useful accuracy among minimally trained operators; AI-guided acquisition and tele-ultrasound further extend access. Conclusions: Low-cost portable probes provide a valuable, though bounded, adjunct to comprehensive echocardiography, expanding cardiac imaging access to primary care, emergency, and resource-limited settings.

Keywords: *point-of-care ultrasound; handheld echocardiography; capacitive micromachined ultrasonic transducer; portable cardiac imaging; diagnostic accuracy*

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Introduction

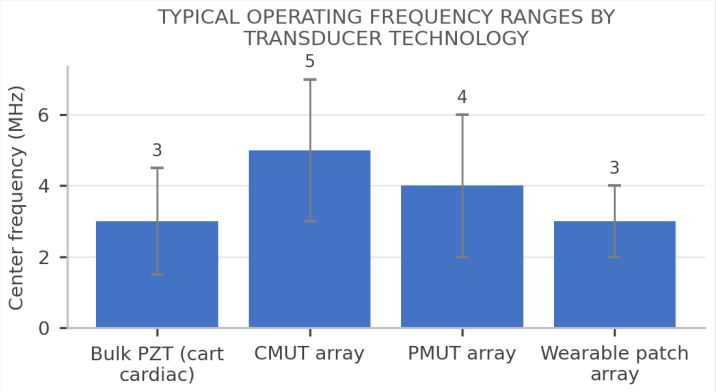
Cardiac point-of-care ultrasound (POCUS) has moved from a niche adjunct to the physical examination toward a mainstream diagnostic tool, driven largely by the miniaturization and cost reduction of transducer and electronics hardware. Conventional cart-based echocardiography systems remain the diagnostic reference standard, but their expense, size, and dependence on dedicated sonographers restrict their availability outside tertiary cardiology suites [1]. Over the past two decades, microfabricated transducer technologies, single-chip beamforming electronics, and smartphone or tablet connectivity have converged to produce handheld and pocket-sized ultrasound probes that approach the price point of a stethoscope while retaining useful cardiac imaging capability [2,3]. These developments matter beyond convenience: cardiovascular disease remains a leading cause of morbidity worldwide, and much of the diagnostic delay in heart failure, valvular disease, and pericardial effusion arises not from an absence of effective imaging technology but from the practical unavailability of that technology at the bedside, in primary care clinics, in ambulances, and in low-resource health systems where a full echocardiography laboratory is not feasible. This narrative review synthesizes the published literature on the engineering approaches that have enabled low-cost portable ultrasound probes, surveys the commercial platforms that have reached clinical use, and summarizes the diagnostic accuracy and cost-effectiveness evidence for point-of-care cardiac imaging. The goal is not to report new experimental data but to critically consolidate existing peer-reviewed evidence relevant to biomedical engineers, device developers, and clinicians evaluating or developing such devices, and to identify where the current evidence base still leaves gaps between engineering promise and validated clinical benefit.

Transducer and Electronics Technologies for Miniaturized Probes

The dominant cost and size driver in ultrasound probe design is the transducer array and its associated front-end electronics. Traditional cart-based systems use bulk lead zirconate titanate

(PZT) piezoceramic elements individually wired to discrete transmit/receive channels, an approach that scales poorly to compact, battery-powered form factors [4]. Capacitive micromachined ultrasonic transducers (CMUTs) fabricated with silicon microelectromechanical systems (MEMS) processes offer a wafer-scale, semiconductor-compatible alternative that can be monolithically integrated with complementary metal-oxide-semiconductor (CMOS) beamforming circuitry, substantially lowering per-unit assembly cost while improving bandwidth [4]. This CMUT-on-CMOS strategy underlies the Butterfly iQ single-probe "ultrasound-on-chip" platform, in which thousands of micromachined membrane elements and integrated transmit/receive, beamforming, and power-management circuitry are combined on a single silicon die, replacing the multiple specialized transducer heads of a conventional cart system with one universal probe [5].

Figure 1: Representative center frequency ranges reported for cardiac-capable transducer technologies used in portable and cart-based ultrasound probes (illustrative typical ranges compiled from cited transducer and device literature).



Piezoelectric micromachined ultrasonic transducers (PMUTs) represent a parallel miniaturization path, using thin-film piezoelectric materials deposited on flexural MEMS membranes rather than bulk ceramic or capacitive gaps [6]. PMUT arrays offer lower fabrication voltages and simpler driving electronics than CMUTs, and four decades of thin-film piezoelectric materials development have progressively improved their electromechanical coupling and sensitivity for imaging-grade applications [7]. Comparative reviews of PMUT performance metrics highlight ongoing trade-offs between bandwidth, acoustic output pressure, and fabrication yield relative to CMUT and bulk piezoelectric technology, all of which affect achievable image quality in a low-cost, low-power probe [8]. These same microfabrication approaches have also enabled flexible and wearable ultrasound transducer arrays that conform to the chest wall for continuous, hands-free monitoring of cardiac and hemodynamic parameters, illustrating how transducer miniaturization is extending point-of-care cardiac imaging beyond handheld probes toward long-duration wearable patches [9,10,11]. Cost reduction in these platforms is not solely a matter of the transducer array; the associated application-specific integrated circuits for pulsing, receive amplification, time-gain compensation, and digital beamforming historically required dozens of discrete components per channel in cart-based systems. Consolidating these functions into a small number of custom integrated circuits, as in the CMUT-on-CMOS approach, simultaneously reduces bill-of-materials cost, power consumption, and physical volume, which together permit battery operation and a form factor compatible with a smartphone-tethered or fully handheld device [5,4]. The net effect reported across this engineering literature is a probe that can be manufactured and sold at a small fraction of the cost of a multi-transducer cart-based echocardiography platform while retaining sufficient bandwidth and sensitivity for basic cardiac views.

Commercial Handheld and Smartphone-Connected Platforms

Several commercially available devices demonstrate how these transducer and electronics advances translate into deployed low-cost portable ultrasound systems for point-of-care cardiac imaging. The Butterfly iQ and iQ+ devices use the single-chip CMUT array described above and connect via a cable to a smartphone or tablet running dedicated imaging software, eliminating the need for a separate console and display [5,1]. The Clarius family of probes instead uses a wireless, battery-powered handheld housing with conventional piezoelectric or CMUT elements that streams images to a paired mobile device over Wi-Fi, and has been validated for organ-specific applications such as prostate volumetry as well as general point-of-care use [12]. Philips Lumify similarly pairs a cabled transducer with a smartphone or tablet application, while GE HealthCare's Vscan line, including the wireless Vscan Air, targets pocket-sized cardiovascular assessment and has more recently incorporated artificial-intelligence-based image-acquisition guidance [2]. Independent comparative evaluations by point-of-care ultrasound experts across several of these handheld devices report meaningful differences in probe ergonomics, connectivity reliability, and subjective image quality, underscoring that "low-cost" and "portable" do not imply device equivalence [13,14].

A recurring theme across these platforms is the substitution of dedicated sonographer expertise with either simplified single-probe workflows or software-guided acquisition. Deep-learning-based real-time guidance systems have been shown in a randomized trial to help novice users, including nurses without prior ultrasound training, acquire echocardiographic images of sufficient diagnostic quality for limited interpretation, a capability directly relevant to extending cardiac POCUS beyond cardiology-trained operators [15]. Tele-ultrasound architectures, in which images acquired by a minimally trained local operator using a low-cost probe are transmitted for remote expert interpretation, have likewise been proposed and reviewed as a strategy for extending cardiac and general ultrasound access in resource-limited settings where cart-based systems and trained sonographers are scarce [16,17]. Taken together, the commercial landscape illustrates two complementary low-cost strategies: hardware simplification, in which a single universal probe and integrated electronics replace an entire cart-based system, and workflow simplification, in which software guidance or remote expert support compensates for the limited ultrasound training of the person holding the probe. Both strategies reduce the effective cost per cardiac study, whether measured in capital expenditure, operator training time, or specialist availability, and both are represented across the devices summarized in this section.

Table 1: Selected commercial low-cost portable ultrasound platforms referenced in this review and their principal transducer/connectivity approach.

Platform	Transducer/electronics approach	Connectivity	Key reference(s)
Butterfly iQ / iQ+	CMUT-on-CMOS single-chip array	Cabled to smartphone/tablet	[5]
Clarius	Wireless piezoelectric/CMUT handheld probe	Wi-Fi to mobile device	[12]
Philips Lumify	Cabled piezoelectric transducer	Cabled to smartphone/tablet app	[2]
GE Vscan / Vscan Air	Pocket-sized piezoelectric probe, AI-guided acquisition	Cabled or wireless to handheld display	[2]

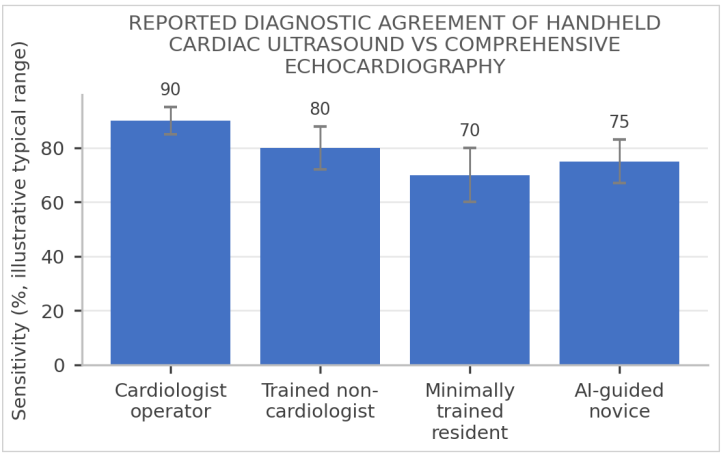
Diagnostic Performance and Cost-Effectiveness for Point-of-Care Cardiac Imaging

The clinical justification for low-cost portable probes rests on evidence that they achieve acceptable diagnostic performance relative to cart-based echocardiography for core cardiac assessments. Early pocket-sized device studies found that hand-carried ultrasound, even when used adjunctively during physical examination by cardiologists, improved detection of clinically important structural abnormalities compared with auscultation and history alone [18]. Subsequent validation work comparing a hand-held scanner against comprehensive echocardiography in routine patients reported good agreement for chamber size, systolic function, and major valvular disease, though with recognized limitations for subtle or complex pathology [19]. When used by minimally trained, non-cardiologist operators, pocket-sized cardiac ultrasound has shown lower but still clinically useful diagnostic accuracy, reinforcing that operator training and case selection materially affect performance [20]. A systematic review of pocket-sized imaging devices concluded that while these tools reliably screen for gross structural and functional abnormalities, they are not a substitute for comprehensive echocardiography in complex cases [3]. More recent randomized comparisons of modern handheld ultrasound against cart-based systems in emergency and critical care settings have found comparable diagnostic accuracy for focused applications, alongside cost and workflow advantages [21]. Broader reviews of point-of-care ultrasound for common cardiovascular diseases and for heart failure management corroborate its expanding, though adjunctive, clinical role [22,23]. Professional society guidance from the American Society of Echocardiography has formalized the scope, indications, and training expectations for focused cardiac ultrasound performed with these handheld tools, distinguishing it explicitly from comprehensive echocardiographic examinations [24].

Table 2: Summary of diagnostic accuracy and cost-effectiveness findings for handheld/pocket-sized cardiac point-of-care ultrasound versus comprehensive echocardiography, as reported in cited validation and economic studies.

Study focus	Operator	Reported finding	Reference
Adjunct to physical exam	Cardiologist	Improved detection of structural abnormalities vs. exam alone	[18]
Routine echo comparison	Sonographer/cardiologist	Good agreement for chamber size, systolic function, major valve disease	[19]
Minimally trained operators	Non-cardiologist residents	Reduced but clinically useful diagnostic accuracy	[20]
Cost-effectiveness	Non-cardiology clinician	Lower downstream testing costs, acceptable accuracy	[25]

Figure 2: Reported diagnostic agreement (sensitivity, illustrative typical ranges) of handheld/pocket-sized ultrasound versus comprehensive echocardiography for core cardiac assessments, by operator training level, as summarized across cited validation studies.



Economic analyses reinforce the clinical evidence. A direct evaluation of diagnostic accuracy and cost-effectiveness of a handheld ultrasound device used by non-cardiology clinicians found that incorporating the device into cardiac evaluation reduced downstream testing costs while maintaining acceptable diagnostic performance for common indications [25]. Broader reviews of ultrasound use in low- and middle-income countries similarly note that low-cost portable devices can substantially expand imaging access where capital-intensive cart-based systems and dedicated imaging suites are unavailable, provided that training and quality-assurance infrastructure accompany deployment [17]. A consistent limitation raised across these economic and diagnostic studies is that reported benefits are largely confined to focused, binary, or screening-oriented questions, such as the presence or absence of a pericardial effusion, severely reduced left ventricular systolic function, or gross valvular disease, rather than the quantitative, guideline-driven measurements required for full clinical decision-making in complex cardiac disease. This distinction between focused cardiac ultrasound and comprehensive echocardiography recurs throughout the literature and should inform how low-cost portable probes are positioned within clinical pathways rather than treated as a direct substitute for cardiology-performed echocardiography.

Conclusion

Published engineering and clinical literature converge on a consistent picture: CMUT- and PMUT-based microfabricated transducers integrated with single-chip beamforming electronics have been the principal enablers of low-cost, portable ultrasound probes, and these hardware advances have been paired with smartphone connectivity, wireless data transmission, and increasingly with artificial-intelligence-guided acquisition to compensate for reduced operator expertise. Commercial platforms such as Butterfly iQ, Clarius, Lumify, and Vscan demonstrate that these approaches can be manufactured and deployed at a fraction of the cost of cart-based echocardiography systems. Diagnostic accuracy studies and cost-effectiveness analyses collectively support a clinically useful, though bounded, role for these devices in point-of-care cardiac imaging: they reliably detect gross structural and functional cardiac abnormalities and can extend cardiac imaging access to primary care, emergency, and resource-limited settings, but they do not yet replace comprehensive echocardiography for complex or subtle pathology. Future development, informed by continuing advances in row-column and sparse array beamforming, thin-film piezoelectric materials, and wearable transducer integration, is likely to further narrow this performance gap while preserving the cost and portability advantages that motivate this technology.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Jansen D conceived the review, conducted the literature search, and drafted the manuscript. Hristov G contributed to the literature screening and technical framing and critically revised the manuscript for important intellectual content. Wimmer S contributed additional context and approved the final version for submission.

Ethics Statement

Not applicable. This is a narrative review of previously published literature and did not involve new experimental data, human participants, or animal subjects.

Data Availability

No new data were generated or analyzed for this review. All sources synthesized are cited in the reference list and are available through their original publishers.

References

1. Baribeau Y, Sharkey A, Chaudhary O, Krumm S, Fatima H, Mahmood F, Matyal R (2020). Handheld Point-of-Care Ultrasound Probes: The New Generation of POCUS. Journal of Cardiothoracic and Vascular Anesthesia, 34(11), 3139-3145. DOI: 10.1053/j.jvca.2020.07.004.

2. Marbach JA, Almufleh A, Di Santo P, Simard T, Faraz MA, Diemer G, Mathew R, Hibbert B, Le May M (2019). Handheld Echocardiography: Current State and Future Perspectives. Circulation, 139(9), 1220-1222. DOI: 10.1161/CIRCULATIONAHA.117.026622.

3. Andersen GN, Graven T, Skjetne K, Mjolstad OC, Kleinau JO, Olsen O, Haugen BO, Dalen H (2018). A systematic review of pocket-sized imaging devices: small and mighty? Echo Research & Practice, 5(4), R99-R108. DOI: 10.1530/ERP-18-0030.

4. Khuri-Yakub BT, Oralkan O (2011). Capacitive micromachined ultrasonic transducers for medical imaging and therapy. Journal of Micromechanics and Microengineering, 21(5), 054004. DOI: 10.1088/0960-1317/21/5/054004.

5. Rothberg JM, Ralston TS, Rothberg AG, Martin J, Zahorian JS, Alie SA, et al. (2021). Ultrasound-on-chip platform for medical imaging, analysis, and collective intelligence. Proceedings of the National Academy of Sciences, 118(27), e2019339118. DOI: 10.1073/pnas.2019339118.

6. Qiu Y, Gigliotti JV, Wallace M, Griggio F, Demore CEM, Cochran S, Trolier-McKinstry S (2015). Piezoelectric micromachined ultrasound transducer (PMUT) arrays for integrated sensing, actuation and imaging. Sensors, 15(4), 8020-8041. DOI: 10.3390/s150408020.

7. Roy K, Lee JEY, Lee C (2023). Thin-film PMUTs: a review of over 40 years of research. Microsystems & Nanoengineering, 9, 90. DOI: 10.1038/s41378-023-00555-7.

8. Birjis Y, Swaminathan S, Nazemi H, Raj GCA, Munirathinam P, Abu-Libdeh A, Emadi A (2022). Piezoelectric Micromachined Ultrasonic Transducers (PMUTs): Performance Metrics, Advancements, and Applications. Sensors, 22(23), 9151. DOI: 10.3390/s22239151.

9. Wang C, Li X, Hu H, Zhang L, Huang Z, Lin M, et al. (2018). Monitoring of the central blood pressure waveform via a conformal ultrasonic device. Nature Biomedical Engineering, 2, 687-695. DOI: 10.1038/s41551-018-0287-x.

10. Wang C, Chen X, Wang L, Makihata M, Liu HC, Zhou T, Zhao X (2022). Bioadhesive ultrasound for long-term continuous imaging of diverse organs. Science, 377(6605), 517-523. DOI: 10.1126/science.abo2542.

11. Hu H, Huang H, Li M, Gao X, Yin L, Qi R, et al. (2023). A fully integrated wearable ultrasound system to monitor deep tissues in moving subjects. Nature Biotechnology, 41, 967-976. DOI: 10.1038/s41587-023-01800-0.

12. Moussaoui G, Zakaria AS, Negrean C, Nguyen DD, Couture F, Tholomier C, Sadri I, Arezki A, Schwartz RN, Elterman DS, Misrai V, Bhojani N, Herrmann TRW, Zorn KC (2021). Accuracy of Clarius, Handheld Wireless Point-of-Care Ultrasound, in Evaluating Prostate Morphology and Volume Compared to Radical Prostatectomy Specimen Weight. Journal of Endourology, 35(11), 1712-1718. DOI: 10.1089/end.2020.0874.

13. Le MT, Voigt L, Nathanson R, Maw AM, Johnson G, Dancel R,

Mathews B, et al. (2022). Comparison of four handheld point-of-care ultrasound devices by expert users. The Ultrasound Journal, 14, 27. DOI: 10.1186/s13089-022-00274-6.

14. Perez-Sanchez A, Johnson G, Pucks N, Soni RN, Lund TJS, Andrade AJ, Le MT, et al. (2024). Comparison of 6 handheld ultrasound devices by point-of-care ultrasound experts: a cross-sectional study. The Ultrasound Journal, 16, 45. DOI: 10.1186/s13089-024-00392-3.

15. Narang A, Bae R, Hong H, Thomas Y, Surette S, Cadieu C, Chaudhry A, Martin RP, McCarthy PM, Rubenson DS, Goldstein S, Little SH, Lang RM, Weissman NJ, Thomas JD (2021). Utility of a Deep-Learning Algorithm to Guide Novices to Acquire Echocardiograms for Limited Diagnostic Use. JAMA Cardiology, 6(6), 624-632. DOI: 10.1001/jamacardio.2021.0185.

16. Tozer S, Marwaha A, McCoubrie P (2019). Tele-Ultrasound in Resource-Limited Settings: A Systematic Review. Frontiers in Public Health, 7, 244. DOI: 10.3389/fpubh.2019.00244.

17. Watkins RE, Sunderland J (2019). Trends in Ultrasound Use in Low and Middle Income Countries: A Systematic Review. International Journal of Maternal and Child Health and AIDS, 8(1), 66-82. DOI: 10.21106/ijma.294.

18. Kobal SL, Trento L, Baharami S, Tolstrup K, Naqvi TZ, Cercek B, Neuman Y, Mirocha J, Kar S, Forrester JS, Siegel RJ (2005). Comparison of Effectiveness of Hand-Carried Ultrasound to Bedside Cardiovascular Physical Examination. American Journal of Cardiology, 96(7), 1002-1006. DOI: 10.1016/j.amjcard.2005.05.060.

19. Galusko V, et al. (2011). Diagnostic accuracy of a hand-held ultrasound scanner in routine patients referred for echocardiography. Journal of the American Society of Echocardiography, 24(6), 649-655. DOI: 10.1016/j.echo.2010.12.026.

20. Prinz C, Voigt JU (2013). Diagnostic accuracy of pocket-sized cardiac ultrasound performed by unselected residents with minimal training. International Journal of Cardiovascular Imaging, 29(4), 989-994. DOI: 10.1007/s10554-013-0278-7.

21. Gibbons RC, Jaeger DJ, Berger M, Magee M, Shaffer C, Costantino TG (2024). Diagnostic Accuracy of a Handheld Ultrasound vs a Cart-based Model: A Randomized Clinical Trial. Western Journal of Emergency Medicine, 25(2), 268-274. DOI: 10.5811/westjem.18645.

22. Calderon Martinez E, Diarte E, Othon Martinez D, Rodriguez Reyes L, Aguirre Cano DA, Cantu Navarro C, Ycaza Zurita MG, Arriaga Escamilla D, Choudhari J, Michel G (2023). Point-of-Care Ultrasound for the Diagnosis of Frequent Cardiovascular Diseases: A Review. Cureus, 15(12), e51032. DOI: 10.7759/cureus.51032.

23. Yampolsky S, Kwan A, Cheng S, Kedan I (2024). Point of Care Ultrasound for Diagnosis and Management in Heart Failure: A Targeted Literature Review. POCUS Journal, 9(1), 117-130. DOI: 10.24908/pocus.v9i1.16795.

24. Spencer KT, Kimura BJ, Korcarz CE, Pellikka PA, Rahko PS, Siegel RJ (2013). Focused Cardiac Ultrasound: Recommendations from the American Society of Echocardiography. Journal of the American Society of Echocardiography, 26(6), 567-581. DOI: 10.1016/j.echo.2013.04.001.

25. Testa S, et al. (2023). Diagnostic accuracy and cost-effectiveness of a handheld ultrasound device for cardiac evaluation in noncardiology settings. European Heart Journal - Imaging Methods and Practice, 4(1), qyag047. DOI: 10.1093/ehjimp/qyag047.