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Developing Probe-Specific Depth of Penetration Baselines for Ultrasound Quality Assurance: A Quality Improvement Study

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ABSTRACT

Depth of penetration (DOP) is the maximum depth at which tissue-mimicking structures remain distinguishable from background noise and is a key indicator of ultrasound image quality and transducer performance. Current quality assurance (QA) guidelines recommend monitoring DOP over time using baseline measurements; however, manufacturers generally do not provide standardized probe-specific reference values, limiting objective longitudinal assessment.

This quality improvement study established manufacturer- and probe-specific DOP baselines using routine QA data from 993 clinical ultrasound transducers representing Canon, GE Healthcare, Philips Healthcare, and Siemens Healthineers systems. Multiple transducer types were evaluated using standardized phantom-based QA procedures.

Baseline DOP values were established for each probe model and compared with annual QA measurements collected over up to seven years to support longitudinal performance assessment.

Manufacturer- and probe-specific DOP baselines were successfully established across all evaluated probe models, providing objective reference values for routine QA. These baselines facilitate longitudinal monitoring, improve consistency in transducer performance assessment, and enable early identification of probes exhibiting deviations from expected performance. Establishing standardized DOP reference values provides a practical framework for ultrasound QA and supports evidence-based equipment maintenance across diverse clinical ultrasound platforms.

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INTRODUCTION

In medical ultrasound, the depth of penetration (DOP) is defined as the maximum distance a transmitted acoustic wave can travel into a biological medium and still return an echo with a sufficient signal-to-noise ratio (SNR) for detection and image reconstruction. Beyond this depth, the returning echoes become indistinguishable from the system's electronic background noise. DOP is influenced by various factors such as the transducer frequency, acoustic power output, system settings, and time-gain compensation.

Routine quality assurance (QA) programs recommended by the American Association of Physicists in Medicine (AAPM), American College of Radiology (ACR), and American Institute of Ultrasound in Medicine (AIUM) identify DOP as a key performance metric for monitoring transducer integrity and overall system performance. These guidelines emphasize establishing baseline measurements and comparing periodic QA results to detect performance degradation over time. The AAPM Ultrasound Task Group No. 1 recommends corrective action when the measured depth of visualization decreases by more than 0.6 cm from baseline and considers deviations exceeding 1.0 cm indicative of a defective system.

Manufacturers generally do not provide standardized manufacturer- or probe-specific DOP reference values. Consequently, many institutions must establish their own baseline measurements, resulting in variability among QA programs and limiting consistency in longitudinal performance assessment. This study addresses this gap by developing manufacturer- and probe-specific DOP baselines to support standardized, objective, and reproducible ultrasound QA.

METHODS AND MATERIALS

Equipment

- Ultrasound Systems: Canon, GE Healthcare, Philips Healthcare, and Siemens Healthineers.
- Transducers: 993 clinical transducers representing linear, curvilinear, phased-array, endo-cavitary, vascular, and specialty probes.
- Phantom: Gammex Sono 403 GS LE Precision Multipurpose tissue-mimicking phantom (1540 m/s; 0.5–0.7 dB/cm/MHz).

QA protocol

- Comprehensive physics testing was conducted in accordance with ACR quality control guidelines, tailored to each transducer's specific clinical application.
- Time-gain compensation (TGC) was set to neutral, and the overall gain was adjusted to achieve uniform background echogenicity.
- All post-processing features were disabled, and the system speed of sound calibration was verified at 1540 m/s

DOP measurement

- DOP was measured using the system's electronic depth calipers with the manufacturer's standard clinical preset for each transducer.
- Measurements were repeated across identical probe models to establish baseline values and evaluate inter-unit reproducibility.

RESULTS

- Manufacturer- and probe-specific DOP baselines were established for 993 ultrasound transducers: Canon, GE Healthcare, Philips Healthcare, and Siemens Healthineers.
- Probe-specific DOP baselines were successfully established for all examined transducers.
- Performance was consistent within probe types and reproducible across identical units, per ACR standards.
- Most probes stayed within the ±0.6 cm action-level tolerance across annual follow-up. Occasional units fell below tolerance (e.g., 18L6 at Year 2) — flagged for service or replacement.
- The established baselines support routine QA and early detection of transducer degradation.

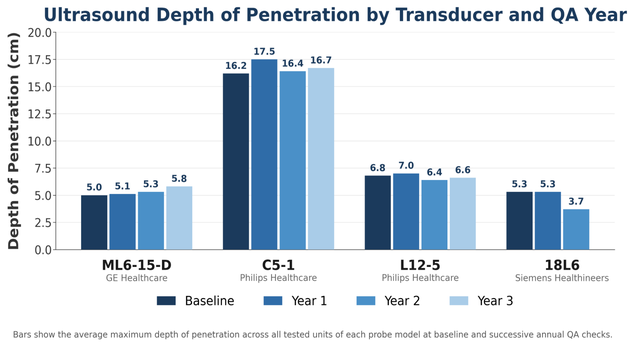

Figure 1. Mean DOP by representative transducer models over successive QA evaluations.

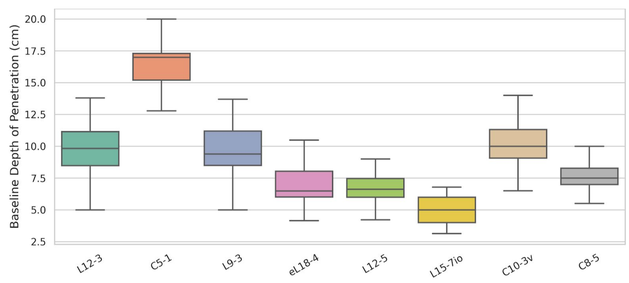

Figure 2. Distribution of Baseline Depth of Penetration by Representative Probe Model.

Ultrasound Depth of Penetration — Baseline & Annual Trending by Probe

Average maximum depth of penetration (cm). n = number of transducer units tested. Yr 1–3 = annual follow-up QA measurements.

Probe	n	Baseline	Yr 1	Yr 2	Yr 3
Philips Healthcare				*35 probes · n=763*	
3D9-3v	6	**8.5**	7.8	—	—
C10-3v	46	**10.1**	11.0	10.0	—
C10-4	2	**7.6**	—	—	—
C12-3	6	**8.6**	—	—	—
C5-1	157	**16.2**	17.5	16.4	16.7
C5-2	3	**17.5**	15.0	—	—
C6-2	6	**15.0**	16.1	—	—
C7-2	3	**14.0**	12.7	—	—
C8-4v	24	**8.8**	9.2	—	—
C8-5	36	**10.0**	8.1	7.7	—
C9-2	21	**13.7**	15.7	17.3	—
C9-4	12	**11.8**	13.2	10.7	—
eL18-4	43	**7.0**	7.1	7.0	7.0
IC5-9-D	3	**6.0**	—	—	—
L12-3	63	**9.8**	10.3	9.7	9.6
L12-4	1	**7.0**	7.0	—	—
L12-5	110	**6.8**	7.0	6.4	6.6
L15-7io	28	**5.0**	4.6	—	—
L17-5	19	**5.6**	5.5	—	—
L18-5	24	**5.2**	5.5	5.5	—
L26-8	1	**4.5**	—	—	—
L8-3	6	**9.3**	8.0	10.0	—
L8-4	3	**9.3**	9.0	—	—
L9-2	3	**11.1**	—	—	—
L9-3	73	**9.6**	9.8	9.2	8.6
S12-4	6	**8.0**	7.2	—	—
S4-1	3	**17.3**	—	—	—
S4-2	1	**16.0**	16.0	—	—
S5-1	23	**15.6**	15.8	—	—
S8-3	5	**13.5**	12.3	—	—
V6-2	2	**16.9**	17.3	—	—
VL13-5	1	**5.6**	—	—	—
X5-1	16	**14.6**	12.8	—	—
X6-1	6	**12.8**	—	—	—
X7-2	1	**10.0**	10.5	—	—
Canon				*5 probes · n=5*	
11C3	1	**10.3**	—	—	—
14L5	1	**5.9**	—	—	—
i18LX5	1	**5.6**	—	—	—
i24LX8	1	**3.9**	—	—	—
i8CX1	1	**14.7**	—	—	—

Probe	n	Baseline	Yr 1	Yr 2	Yr 3
GE Healthcare				*20 probes · n=110*	
9L-D	20	**11.3**	12.1	11.8	11.8
C1-5-D	17	**13.5**	13.4	14.4	15.6
C1-6-D	4	**15.9**	—	—	—
C4-1	4	**15.3**	17.5	—	—
C4-8-D	3	**15.7**	16.5	—	—
C6-2	3	**16.3**	16.2	17.6	17.5
IC5-9-D	3	**8.8**	—	—	—
L10-5	2	**7.5**	8.5	7.0	—
L14-5w	3	**9.3**	10.0	—	—
L2-9-D	10	**10.3**	—	—	—
L20-5	1	**3.6**	3.7	—	—
L3-12-D	1	**8.0**	—	—	—
L6-24-D	2	**3.7**	—	—	—
L8-18i-D	5	**5.5**	—	—	—
M5Sc-D	1	**15.8**	—	—	—
ML4-20-D	5	**5.8**	—	—	—
ML6-15-D	19	**5.0**	5.1	5.3	5.8
RM6C	4	**14.9**	16.5	—	—
RSP6-16-D	1	**4.0**	7.2	5.1	—
S1-5	2	**15.6**	—	—	—
Siemens Healthineers				*24 probes · n=114*	
10L4	3	**9.8**	9.7	9.7	—
10V4	2	**10.2**	—	—	—
11M3	1	**14.0**	—	—	—
12L3	2	**7.5**	—	—	—
12L4	1	**6.9**	—	—	—
14L5	13	**5.4**	5.4	6.0	—
18H6	2	**5.1**	5.0	—	—
18L6	20	**5.3**	5.3	3.7	—
18L8	1	**6.5**	5.0	—	—
4C1	3	**16.6**	—	—	—
4P1	2	**17.6**	—	—	—
4V1	11	**17.1**	17.1	16.0	—
5C1	7	**16.6**	15.6	15.6	—
5V1	1	**18.0**	—	—	—
6C1	5	**17.4**	18.0	—	—
6C2	11	**17.6**	17.6	17.7	—
8C3	1	**13.0**	—	—	—
9C3	2	**12.6**	—	—	—
9EC4	2	**8.0**	8.0	—	—
9EVF4	1	**10.0**	—	—	—
9L4	15	**11.5**	12.3	14.0	—
9VE4	1	**8.8**	—	—	—
CH4-1	2	**16.0**	—	—	—
EV-8C4	5	**10.1**	—	—	—

Figure 3. Probe-specific DOP baseline reference values (all evaluated probes).

DISCUSSION

Establishing manufacturer- and probe-specific DOP baselines addresses an important need by providing objective reference values for ultrasound quality assurance. Because DOP varies substantially with transducer frequency, design, and clinical application, individualized baselines are more sensitive to true performance degradation than generic acceptance criteria.

This periodic, comparative approach aligns closely with standard U.S. quality assurance practices. For example, the AAPM Ultrasound Task Group No. 1 triggers corrective action when a probe deviates by more than 0.6 cm from its baseline and classifies any shift exceeding 1 cm as a defect; similarly, the AIUM framework categorizes transducer degradation to ensure underperforming units are systematically removed from clinical service. Furthermore, pooled measurements from 993 transducers across four manufacturers demonstrate that baseline differences among probe models are expected and primarily reflect variations in transducer design, imaging presets, and clinical application rather than hardware malfunction.

Implementing probe-specific baselines successfully isolates expected baseline variability from clinically significant drift, enabling earlier detection of performance degradation before action thresholds are exceeded. These manufacturer- and probe-specific reference values provide a practical framework for standardized longitudinal quality assurance and support more consistent monitoring of ultrasound transducer performance across diverse clinical systems.

CONCLUSIONS

Manufacturer- and probe-specific DOP baselines were established for 993 ultrasound transducers across four manufacturers. Probe-specific baselines provide objective reference values for longitudinal ultrasound quality assurance and improve detection of clinically significant performance changes.

Routine comparison with baseline measurements supports early identification of transducer degradation and timely corrective action.

This framework strengthens standardized ultrasound QA and may improve consistency across clinical imaging programs.

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