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Abstract

Complex geometries, boundaries, large grain size, and anisotropic weld metal together with tight and branching service-induced cracks make the ultrasonic testing (UT) of dissimilar metal welds (DMWs) challenging. To address this research need, the Program to Assess the Reliability of Emerging Nondestructive Techniques (PARENT) was established by the U.S. Nuclear Regulatory Commission (U.S. NRC) as a follow-on to the Program for Inspection of Nickel Alloy Components (PINC). The U.S. NRC executed the in-kind agreements with organisations from Finland, Japan, Korea, Sweden and Switzerland in 2012.

A series of blind and open round robin tests (RRT) was conducted and the results were documented in public reports. The objective of blind RRT was to evaluate the effectiveness of the established, qualified non-destructive examination (NDE) procedures for detection and sizing of primary water stress corrosion cracking in DMWs. The objective of open RRT was to evaluate novel and emerging NDE techniques to find the most promising new techniques for the inspection of DMWs.

In PARENT blind testing, outer diameter (OD) PAUT procedures showed better performance than OD conventional UT procedures for SBDMWs as measured by POD and depth sizing root mean square error (RMSE). However, PARENT results indicate significant variability in performance both for UT and PAUT procedures employing similar techniques on SBDMWs.

Comparison of PINC results to PARENT blind RRT results for SBDMW blocks with UT showed that both PAUT and time-of-flight diffraction (TOFD) procedures performed better in PARENT. Overall depth sizing RMSE of SBDMWs was improved for PARENT, although the spread between best and worst sizing results was larger than for PINC. Length sizing also appeared to have improved in PARENT relative to PINC based on RMSE.

Several issues related to the non-destructive testing of DMWs still need research, thus a new international agreement by U.S. NRC to establish the Program for Investigation of NDE by International Collaboration (PIONIC) was signed in the beginning of 2019. One goal is to study the application of virtual flaws together with modelling and simulation in inspection development.

1. Introduction

The in-service inspection (ISI) carried out by non-destructive testing (NDT) is required to ensure the safe and sustainable operation of nuclear power plants (NPPs). NDT aids to evaluate the suitability of an NPP component for operation. Thus, the reliability of NDT procedures is essential.

Dissimilar metal welds (DMWs) containing Ni-based Alloys 600, 182 and 82 are found susceptible to stress corrosion cracking (SCC), often referred to as primary water stress corrosion cracking (PWSCC) in pressurized water reactors (PWRs) and interdendritic stress corrosion cracking (IDSCC) in boiling water reactors (BWRs) [1,2]. PWSCC degradation has resulted in breaches of the pressure boundary and caused leakage in several DMWs [3].

Complex geometries, boundaries, large grain size, and anisotropic weld metal together with tight and branching service-induced cracks make especially the ultrasonic testing (UT) of DMWs challenging. Proper planning of UT well in advantage before an ISI is a key to a successful examination. ISI should be able to detect degradation such as cracking and wall thinning before degradation affects the component's integrity and functional performance.

Access from the outside surface, good performance in detecting planar flaws, possibility for height sizing and avoidance of radiation are advantages of UT especially in detection and sizing of inside surface breaking cracks. UT techniques are constantly under development together with evolving material technology.

VTT has participated in the international PINC and PARENT programs. The PINC program was studying the crack morphology and NDE responses of PWSCC. Together with that, the capability of various commercial and emerging NDE methods to detect and size PWSCC were studied [3]. The follow-up program PARENT assessed NDE techniques for detecting and characterizing service-induced cracks and distinguishing them from other types of flaws. The capability of available and emerging NDE techniques to detect and size such cracks was assessed quantitatively. Results of these RRTs are documented in public reports [5, 6,7].

2. Experiments

2.1 Test blocks

PARENT test blocks with welds of Ni-based alloys 82 and 182 represented small bore (SBDMW) and large bore (LBDMW) test blocks together with bottom-mounted instrumentation nozzles (BMI). In addition, one weld overlay (WOL) was included in blind testing. Test blocks contained simulated flaws including laboratory-grown stress corrosion cracks (SCC), thermal fatigue cracks (TFC), mechanical fatigue cracks (MFC), tightened weld solidification cracks (SC), welding defects and electrical discharge machining (EDM) notches.

VTT conducted blind testing for two SBDMW test blocks with ODs of 289 mm and 815 mm and thicknesses of 35 mm and 39.5 mm. The OD range of the three open SBDMW test blocks that VTT tested was 286–387 mm and thickness range 32–47 mm. In addition, VTT tested the seven open flat bar (FB) test blocks with thickness of 30.3 mm. Figure 1 shows examples of open piping and FB test blocks.

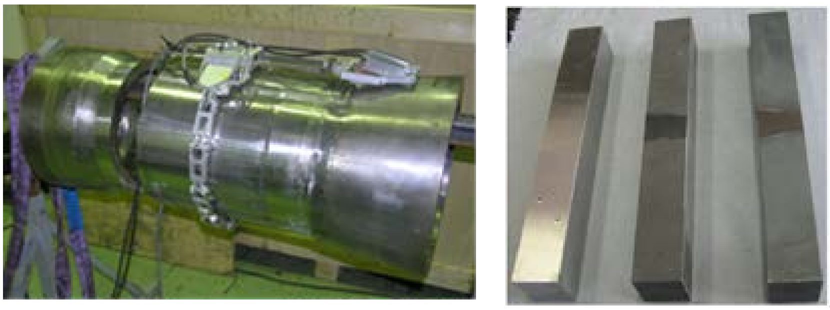

Figure 1. On the left: PAUT scanning of two open piping test blocks. On the right: example of FB test blocks.

2.2 Inspection procedures

2.2.1 Blind testing procedures

Inspection procedure types in blind testing were based on PAUT, conventional UT, eddy current and TOFD techniques or combination of them. VTT's procedure provided by Zetec utilized PAUT technique with 1.5 MHz transmitter-receiver (TR) probes. Both longitudinal (LW) and shear wave (SW) modes were applied. Overview of the technique is shown in Table 1.

Table 1. Overview of PAUT technique used at VTT in blind testing.

Flaw orientation	Beam direction	Focal law type	Refracted angles	Skew angles
Circumferential	TR LW	Linear	45º, 60º, 70º	0º
	TR SW		45º, 60º	
Axial	TR LW	Sectorial	22.5º, 30º, 37.5º, 45º (OD < 304.8 mm) 25º, 35º, 45º, 55º (OD ≥ 304.8 mm and < 1016 mm)	-25º to 25º, resolution 2.5º
	TR SW		35º, 40º,45º (OD < 304.8 mm) 35º, 45º,55º (OD ≥ 304.8 mm)	

2.2.2 Open testing procedures

Inspection procedure types in open testing contained PAUT, UT, advanced phased array ultrasonic testing (ADVPAUT), nonlinear ultrasonic testing (NLUT), guided ultrasonic waves, laser ultrasound visualization, microwave near-field microscopy, radiographic testing (RT) and ultrasound infrared tomography (UIR).

VTT established two teams for open testing. Team 114 used the same procedure as VTT's blind testing team. As VTT performed open before blind testing, open testing worked as an implementation and training of the procedure at VTT. Procedure of Team 122 utilized linear and sectorial PAUT techniques shown in Table 2 with 1.5 MHz TR probe.

Table 2. Overview of PAUT techniques used by VTT's Team 122 in open testing.

Flaw orientation	Beam direction	Focal law type	Refracted angles	Skew angles
Circumferential	TR LW	Linear	45º, 50º, 55º, 60º	0º
		Sectorial	40º–70º, resolution 1º	

2.3 Data processing

2.3.1 Data reporting

The teams reported the results on technique datasheets and inspection summary datasheets. For example, if an ultrasonic inspection procedure consists of three refracted angles, which may be used separately for detection, length sizing and depth sizing, this information gives three individual technique datasheets. This information is combined in completion of inspection summary datasheet [5].

PARENT utilized the same scoring criteria as PINC. A tolerance box shown in Figure 2 where δX = δY = 10 mm was added to flaw true-state dimensions to avoid penalizing minor positioning errors [5].

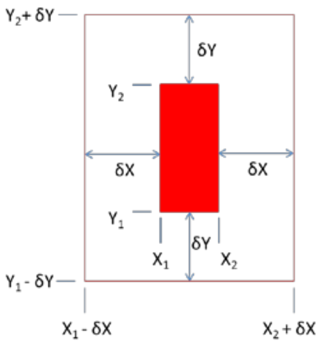

Figure 2. Tolerance (δX and δY) applied to flaw true state (in red) dimensions in PARENT [5].

2.3.2 Data analysis

Detection performance was evaluated with probability of detection (POD) and false call probability. POD evaluation was done only for blind testing, because in open testing the teams were provided with true-state information of flaws. Sizing performance (depth and length) was analysed using linear regression.

3. Results

3.1 Blind testing results

This section presents a short overview of the blind UT results of SBDMWs, i.e. the test block category that VTT tested.

3.1.1 Detection performance

Table 3 contains the summary of POD versus depth for procedures, with rather good performance of the VTT's procedure.

Table 3. POD (%) vs depth for procedures applied to SBDMWs (OD access) [5].

Procedure	NOBS	0 mm	5 mm	10 mm	15 mm	30 mm
PAUT.108.1	28	5	35	84	98	100
PAUT.115	28	6	58	97	100	100
PAUT.126.1	28	3	12	33	65	99
PAUT.128 (VTT)	28	11	51	89	99	100
UT.108	28	6	33	81	97	100
UT.126	28	8	14	23	35	76
UT.134.2	28	9	28	59	84	100
UT.25[(a)]	12	11	17	26	37	74
UT.TOFD.117	28	4	42	92	99	100
All	236	6	28	69	93	100
[(a)] UT.25 was not a qualified procedure. (NOBS = number of observations)						

Overall POD for all procedures applied to SBDMW blocks, presented in Figure 3 and Figure 4, shows clearly better detection performance for PAUT than for UT.

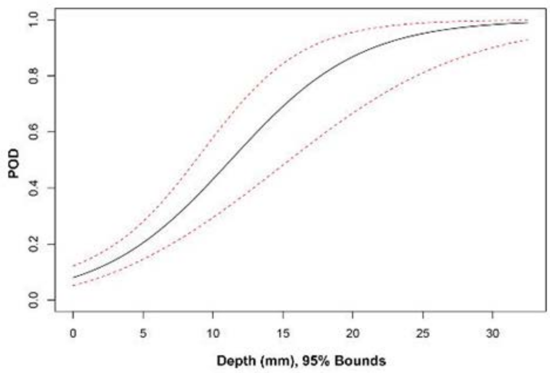

Figure 3. POD versus depth (mm) for UT procedures applied to SBDMW test blocks (OD access) [5].

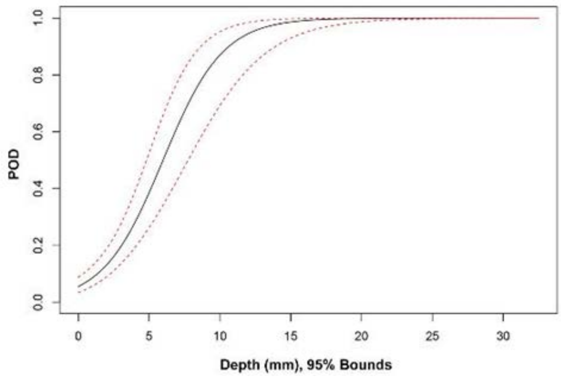

Figure 4. POD versus depth (mm) for PAUT procedures applied to SBDMW test blocks (OD access) [5].

3.1.2 Depth sizing results

Depth sizing errors for ultrasonic procedure types are presented in Table 4. These results indicate the best performance for PAUT. However, none of the procedure types met the ASME Code requirement for depth sizing accuracy of 3.2 mm. Table 5 presents the depth sizing error for ultrasonic procedures. The performance of VTT's procedure with RMSE 4.2 mm left some room for improvement. VTT's bias 1.4 mm indicates slight tendency of oversizing the flaws.

Table 4. Depth sizing errors for UT procedure types on SBDMWs (OD access) [5].

Procedure type	NOBS	Bias (mm)	RMSE (mm)
PAUT	84	-0.9	3.6
UT	54	-3.5	7.9
UT.TOFD	19	0.6	4.1
All	157	-1.6	5.5

Table 5. Depth sizing errors for UT procedures on SBDMWs (OD access) [5].

Procedure	NOBS	BIAS (mm)	RMSE (mm)
PAUT.108.1	21	-1.7	2.4
PAUT.115	25	-0.3	1.8
PAUT.126.1	14	-5.0	5.9
PAUT.128 (VTT)	24	1.4	4.2
UT.108	20	-1.0	4.2
UT.126	10	-4.1	7.1
UT.134.2	21	-4.9	9.5
UT.25[(a)]	3	-8.8	13.9
UT.TOFD.117	19	0.6	4.1
[(a)] UT.25 was not a qualified procedure.			

The regression plots for depth sizing using all PAUT procedures and VTT's procedure applied to SBDMWs are presented in Figure 5. These plots indicate slight oversizing of shallow flaws and slight undersizing of deep flaws.

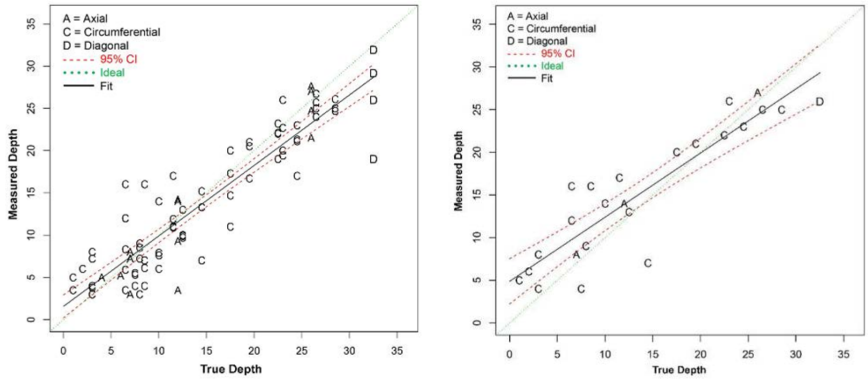

Figure 5. Depth sizing fit (mm) for PAUT procedures (left) and for procedure PAUT.128 (right) applied to SBDMWs (OD access) in PARENT blind testing [5].

3.1.3 Length sizing results

Summary of length sizing errors for ultrasonic procedure types indicated no substantial difference between procedure types. VTT's procedure performed well with RMSE of 12.0 mm. The bias of 10.5 mm indicated clear tendency of oversizing the flaws.

The regression plots for length sizing using all PAUT procedures and VTT's procedure applied to SBDMWs in Figure 6 indicate slight oversizing of shallow flaws for all procedures, and regular slight oversizing of all flaws for VTT's procedure [5].

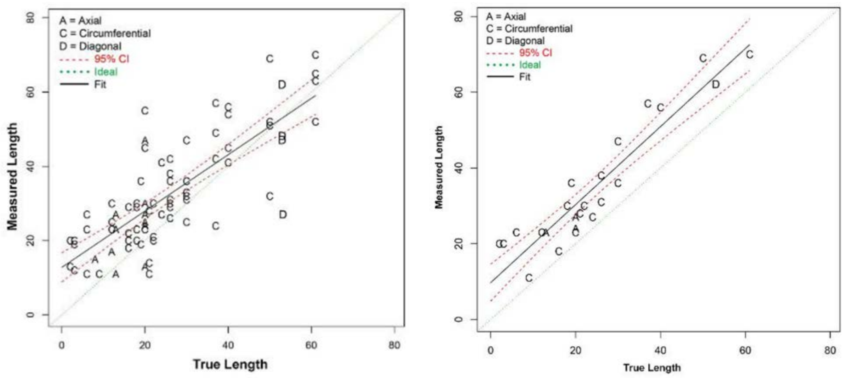

Figure 6. Length sizing fit (mm) for PAUT procedures (left) and for procedure PAUT.128 (right) applied to SBDMWs (OD access) in PARENT blind testing [5].

3.2 Open testing results

This section provides a short overview of the open testing UT depth sizing results of SBDMWs and FBs, i.e. the two test block categories that VTT tested.

Depth sizing results for UT procedure types and all UT procedures in PARENT open testing are shown in Table 6 and Table 7, respectively. VTT's procedures produced depth sizing RMSEs of less than the ASME Code requirement for depth sizing accuracy (3.2 mm). There was no difference in performance of linear and sectorial scan techniques (122.1 and 122.2, respectively) [7].

Table 6. Depth sizing results for procedure types applied to SBDMW and FB test blocks with OD access [7].

Procedure type	NOBS	Bias (mm)	RMSE (mm)
ADVPAUT	57	2.7	5.3
NLUT	38	0.7	6.7
PAUT	79	0.3	3.4
UIR	6	1.0	3.4
UT	11	-0.0	2.1
All	205	1.0	4.6

Table 7. Depth sizing results for procedures applied to SBDMW and FB test blocks with OD access [7].

Procedure	NOBS	Bias (mm)	RMSE (mm)
HHUT 27.1	9	3.2	11.1
HHUT 27.2	7	3.1	7.1
LASH.18	9	-1.7	3.3
PAATOFD.29.0	13	0.8	4.6
PAATOFD.29.1	7	3.6	5.5
PAATOFD.29.2	7	3.9	5.8
PATP.29	9	2.4	6.6
PAUT.114	26	0.2	2.8
PAUT.122.1	7	0.4	0.9
PAUT.122.2	7	-0.0	1.1
PAUT.131.1	5	4.1	8.8
PAUT.131.2	16	0.3	0.6
PAUT.131.4	8	-0.1	0.4
PAUT.20	10	-0.6	5.4
SAFT.17	21	3.3	4.8
SHPA.6.1	5	1.6	1.9
SHPA.6.2	4	-5.2	5.4
SHPA.6.3	4	1.0	1.4
UIR.20	6	1.0	3.4
UT.104	11	-0.0	2.1
HHUT = higher harmonic ultrasonic technique; LASH = large amplitude excitation subharmonic UT; PAATOFD = phased array asymmetrical beam time-of-flight diffraction; PATP = phased array twin probe; SAFT = synthetic aperture focusing technique; SHPA = subharmonic phased array; UIR = ultrasound infrared tomography			

Figure 7 presents the depth sizing regression for all PAUT procedures and for VTT's procedure PAUT.114 for SBDMWs. These plots indicate slight oversizing of the shallow flaws and slight undersizing of deep flaws [7]

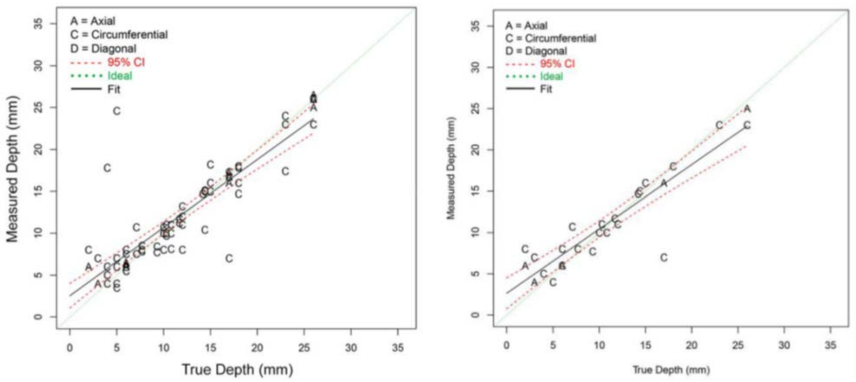

Figure 7. Depth sizing regression for PAUT procedures (left) and for procedure PAUT.114 (right) on SBDMW and FB test blocks in PARENT open testing with OD access. [7].

Figure 8 shows an example of two data image responses from VTT's inspection. The inspection was performed by linear scanning with TRL probe at 60° for test block P28 and 50° for test block P32. Arrows in the image on the left highlight two possible crack tip signals. The white circle in the image on the right indicates the tip region with difficult separation of the tip response from noise.

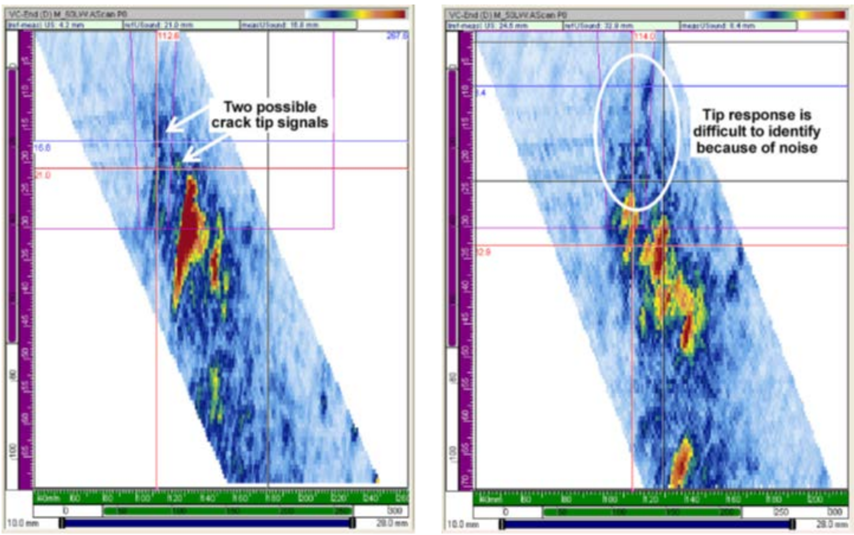

Figure 8. Data image response for PAUT.122.1 inspection of SCC flaws in FB test blocks P28 (left) and P32 (right) [7].

4. Discussion

4.1 Comparison of PARENT vs. PINC

Table 8 compares PINC results [1] to the PARENT blind RRT for SBDMW blocks with ultrasonic techniques. Table indicates that both PAUT and UT.TOFD procedures have performed better in PARENT than in PINC [5].

Comparison of sizing results on SBDMW test blocks for both PINC and PARENT is shown in Table 9. Overall depth sizing RMSE has improved for PARENT, although the spread between best and worst sizing performers is larger for PARENT than PINC. Length sizing also appears to have improved in PARENT relative to PINC and the spread between best and worst length sizing performers is narrower for PARENT relative to PINC [5].

Table 8. Comparison of PINC and PARENT detection results as POD (%) versus depth for SBDMW test blocks [5].

	0 mm	**5 mm**	**10 mm**	**15 mm**
PINC UT	6	36	51	67
PARENT UT	8	20	43	69
PINC PAUT	6	36	51	66
PARENT PAUT	6	39	87	99
PINC UT.TOFD	9	44	53	61
PARENT UT.TOFD	4	42	92	99

Table 9. Comparison of PINC and PARENT depth and length sizing error for SBDMW test blocks [5].

	Depth sizing RMSE (mm)		
	All	**Best**	**Worst**
PINC	7.1	3.2	10.1
PARENT	5.5	1.8	13.9
	Length sizing RMSE (mm)		
	All	**Best**	**Worst**
PINC	25.0	3.6	91.0
PARENT[(a)]	12.1	8.0	22.6
[(a)] For PARENT evaluation, two outliers were excluded from length sizing.			

4.2 Reliability of results

Laboratory circumstances are easier than the actual ISI work, thus, techniques in this study may give optimistic results. It is also notable that the number of the results is limited. Some of the teams were university teams so they do not have experience of actual field inspections. In addition, discussion about the relevance of the flaws will continue in the future work.

4.3 Future NDE work

The U.S. NRC has established the Program for Investigation of NDE by International Collaboration (PIONIC). The objectives of PIONIC are:

1. Share results of related NDE research.
2. Evaluate the capability of NDE modelling and simulation.
3. Perform analysis of flaw relevance on NDE responses.
4. Develop guidance for extending NDE performance during testing to actual field inspection.
5. Identify NDE techniques for monitoring material degradation.
6. Evaluate the reliability of NDE methods used to inspect nuclear power plant (NPP) systems and components.

5. Conclusions

Based on blind testing results, OD PAUT procedures performed better than OD conventional UT procedures for SBDMWs. PARENT results indicate substantial improvement in OD PAUT performance for SBDMWs, compared with PINC performance data. However, PARENT results indicate significant variability in performance for UT procedures employing similar techniques and for PAUT procedures employing similar techniques on SBDMWs [5].

Two of nine procedures applied for depth sizing on SBDMW test blocks by OD access in the Blind test met the intent of the ASME Code, Section XI requirement of RSME within 3.2 mm. Difficulty in identifying crack tip signals with low SNR in blind test conditions reduces the depth sizing accuracy and reliability of UT procedures [5, 7].

Eight of nine procedures applied for length sizing on SBDMW test blocks by OD surface access in the Blind test met the intent of ASME Code, Section XI requirement of RMSE within 19 mm [5].

In open testing, a general trend is observed for oversizing shallow flaws and undersizing deep flaws. Exception for that are the ADVPAUT procedure types and NLUT procedures based on sub-harmonic techniques with a more consistent depth sizing error. ADVPAUT procedure types do not exhibit better overall depth sizing accuracy than PAUT procedure types in this study based on RMSE. Overall, based on RMSE, NLUT procedure types do not exhibit better overall depth sizing accuracy in comparison to ADVPAUT and PAUT procedure types [7].

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