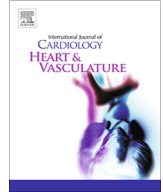




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Head-to-head comparison of quantitative measurements between intravascular imaging systems: An in vitro phantom study



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ABSTRACT

Introduction: The present study aimed to compare the accuracy of quantitative measurements by contemporary intravascular imaging systems including optical frequency domain imaging (OFDI), frequency domain optical coherence tomography (FD-OCT), and 6 intravascular ultrasound (IVUS) systems.

Methods: We imaged five cylindrical phantom models made from an acrylic resin with known lumen diameters (1.51, 2.03, 3.04, 4.04, and 5.04 mm, respectively) using OFDI (FastView and LUNAWAVE, Terumo), FD-OCT (Dragonfly JP and ILUMIEN OPTIS, Abbott Vascular), and 6 mechanically rotating IVUS systems including a system, two 40-MHz, one 45-MHz, two 60-MHz and one broad-band frequency IVUS systems. The OFDI, FD-OCT, and IVUS images were obtained using automated motorized pullback in a tank filled with 37-degree Celsius saline and, in cases of OFDI and FD-OCT, contrast-saline mixture (1:1 ratio) and contrast under the system setting of the refractive index for the corresponding flush medium.

Results: All the imaging systems showed good accuracy and excellent precision of lumen measurement with the relative differences between the measured diameter and actual phantom diameter being ranging from -2.9% to 8.0% and minimum standard deviations of the measured diameters (≤ 0.02 mm).

Conclusion: The present study demonstrated that contemporary intravascular imaging systems including OFDI, FD-OCT, and IVUS provided clinically acceptable accuracy and excellent precision of quantitative lumen measurement in phantom models in vitro across a wide range of dimensions. Future research to confirm these findings in vivo are warranted.

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1. Introduction

Previous studies have reported that intravascular ultrasound (IVUS) overestimated lumen dimensions compared with optical coherence tomography (OCT) [1,2]. Recently, new IVUS systems with high or broad-band frequencies have been introduced; however, there has been no comprehensive validation study that compares quantitative measurement between those contemporary intravascular imaging systems. Hence, this study aimed to compare the accuracy of quantitative measurements by optical frequency domain imaging (OFDI), frequency domain optical coherence tomography (FD-OCT), and 6 IVUS systems.

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2. Methods

We imaged five cylindrical phantom models made from an acrylic resin with known lumen diameters (1.51, 2.03, 3.04, 4.04, and 5.04 mm, respectively) using OFDI (catheter: FastView and console: LUNAWAVE, Terumo Corporation), FD-OCT (Dragonfly JP and ILUMIEN OPTIS, Abbott Vascular), and 6 mechanically rotating IVUS systems including the system 1) 40-MHz IVUS (ViewIT and VISICUBE, Terumo Corporation), 2) 40-MHz IVUS (OptiCross and iLab, Boston Scientific Corporation), 3) 45-MHz IVUS (Refinity and CORE Mobile, Philips Volcano), 4) 60-MHz IVUS (AltaView and VISICUBE, Terumo Corporation), 5) 60-MHz IVUS (OptiCross HD and iLab, Boston Scientific Corporation), and 6) broad-band frequency IVUS (DualPro and MAKOTO, Nipro) [3–8]. Each of the IVUS systems consist of a flexible monorail catheter with a mechanical rotational (1800 rpm) single transducer probe (annular array) at its tip that emits ultrasound waves in the 40–60 MHz range or broad band of frequencies and an electronics console to recon-

struct the image [8]. OFDI/FD-OCT image acquisition is analogous to IVUS, except they use near-infrared light instead of ultrasound [8]. The OFDI, FD-OCT, and IVUS images were obtained using automated motorized pullback in a tank filled with 37-degree Celsius saline and, in cases of OFDI and FD-OCT, contrast-saline mixture (1:1 ratio) and contrast under the system setting of the refractive index for the corresponding flush medium as previously described (3). The imaging catheter pullback was performed using the dedicated automated pullback device of each system at a speed of 0.5 mm/s for IVUS, 20 mm/s for OFDI or 18 mm/s for FD-OCT. To explore the effect of the pullback speed on quantitative measurement, we performed additional pullbacks with AltaView IVUS catheters at 3 mm/s and 9 mm/s. OFDI, FD-OCT, and IVUS images were continuously recorded on each console and exported as a DICOM format. All the images were analyzed offline at Stanford Cardiovascular Core Analysis Laboratory using a commercially available image analysis software (echoPlaque; INDEC Medical Systems, Santa Clara, CA). Five optimally analyzable cross sections were selected in each phantom model in each imaging system, and lumen contours of the selected cross sections were manually traced. Mean value and standard deviation of measured average diameters (derived from the delineated cross-sectional lumen area) and the difference and the relative difference between measured diameter and actual phantom diameter were presented. Among the 6 IVUS catheters (OptiCross, OptiCross HD, ViewIT, AltaView, DualPro, and Refinity), DualPro and Refinity have relatively larger catheter diameter at the imaging window (3.2 Fr and 3.0 Fr, respectively versus 2.6 Fr [the other IVUS catheters]), therefore we were unable to measure the 1.51- and 2.03-mm diameter phantom models by using the 2 IVUS catheters. Hence, we report the quantitative measurements of 3.04-, 4.04-, and 5.04 -mm phantom models assessed by the 2 IVUS systems just for reference purpose. The other imaging systems have 2.6 Fr in diameter at the imaging window and measurements of the 5 phantom models were performed twice using 2 different catheters. To simulate IVUS measurement in a blood environment, measured diameters by IVUS were adjusted for the difference between the speed of sound in the 37 degrees Celsius saline (1522.3 m/s) and the theoretical speed of sound in blood employed in the IVUS sys-

tems [3] by using following formula: adjusted diameter = (measured diameter – catheter diameter) × (speed of sound in saline / speed of sound in blood) × catheter diameter. We applied the following speed of sound in blood for the calculation: 1562.5 m/s for IVUS of the Terumo Corporation, 1560 m/s for the IVUS of the Boston Scientific Corporation, NIPRO, and Philips Volcano.

3. Results

The measurements of OFDI, FD-OCT and 6 IVUS systems are summarized in Figs. 1, 2, Tables 1, and 2. All the imaging systems showed good accuracy and excellent precision of lumen measurement with the relative differences between the measured diameter and actual phantom diameter being ranging from –2.9% to 8.0% and minimum standard deviations of the measured diameters (≤ 0.02 mm). After adjusting for the speed of sound in saline and blood, the relative differences between the measured diameter by IVUS and phantom diameter ranged between –4.5% to 6.8% (Table 3).

4. Discussion

The present study compared quantitative measurements between contemporary intravascular imaging systems currently available in the catheterization laboratory and showed clinically acceptable quantitative accuracy and excellent precision in all the intravascular systems including OFDI, FD-OCT, and IVUS across a wide range of phantom diameters.

The OPUS-CLASS study showed that in a phantom model (lumen diameter 3.08 mm; lumen area 7.45 mm²), IVUS (Atlantis SR Pro, Boston Scientific Corporation) overestimated the lumen area and was less reproducible compared with FD-OCT (C7-XR OCT imaging system, LightLab Imaging/St. Jude Medical) (8.03 ± 0.58 mm² vs. 7.45 ± 0.17 mm²; p less than 0.001) [1]. Based on that study and others [1,2], IVUS has been considered to overestimate vessel dimension by around 10% than OCT. Unlike previous studies [1–4,9], the present study comprehensively compared 6 different IVUS systems as well as OFDI and FD-OCT measuring phantom models with 5 different dimensions and showed excellent accuracy

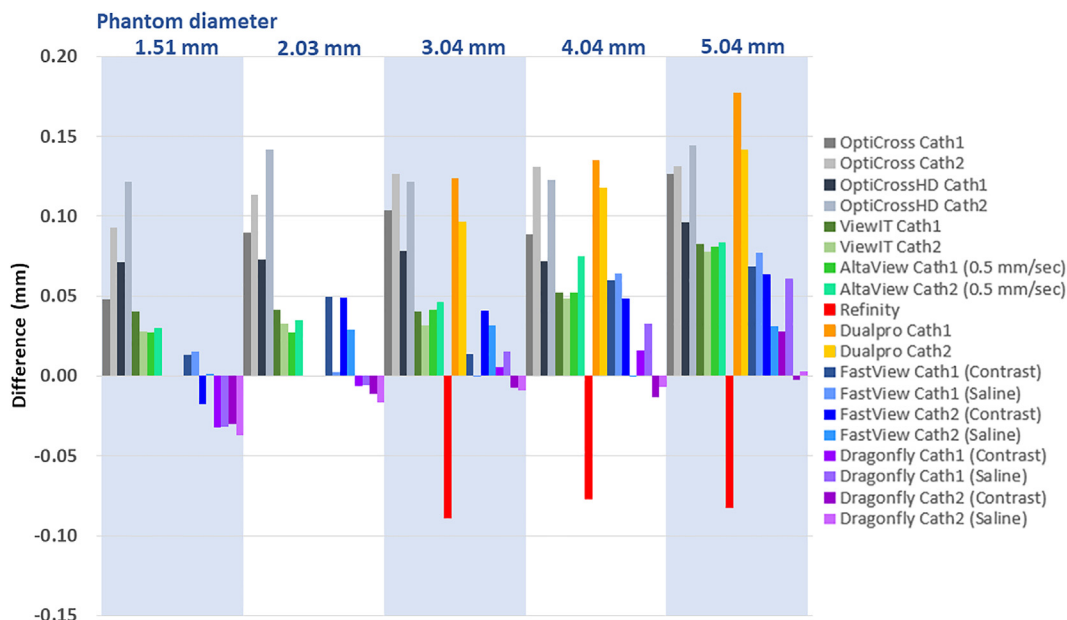


Fig. 1. Difference between measured lumen diameter and actual phantom diameter. The difference was calculated as the measured lumen diameter minus the actual phantom diameter. Cath indicates catheter.



Fig. 2. Relative difference between measured lumen diameter and actual phantom diameter. The relative difference was calculated as the measured lumen diameter minus the actual phantom diameter divided by the actual phantom diameter. Cath indicates catheter.

Table 1
Lumen diameter measured by IVUS imaging systems.

IVUS	Pullback	Phantom Diameter				
		1.51 mm	2.03 mm	3.04 mm	4.04 mm	5.04 mm
OptiCross Catheter 1	0.5 mm/s	1.56 ± 0.02 (3.2%)	2.12 ± 0.02 (4.4%)	3.14 ± 0.01 (3.4%)	4.13 ± 0.01 (2.2%)	5.17 ± 0.01 (2.5%)
OptiCross Catheter 2	0.5 mm/s	1.60 ± 0.01 (6.1%)	2.14 ± 0.02 (5.6%)	3.17 ± 0.01 (4.2%)	4.17 ± 0.01 (3.2%)	5.17 ± 0.01 (2.6%)
OptiCrossHD Catheter 1	0.5 mm/s	1.58 ± 0.01 (4.7%)	2.10 ± 0.02 (3.6%)	3.12 ± 0.00 (2.6%)	4.11 ± 0.01 (1.8%)	5.14 ± 0.01 (1.9%)
OptiCrossHD Catheter 2	0.5 mm/s	1.63 ± 0.01 (8.0%)	2.17 ± 0.02 (7.0%)	3.16 ± 0.01 (4.0%)	4.16 ± 0.01 (3.0%)	5.18 ± 0.00 (2.9%)
ViewIT Catheter 1	0.5 mm/s	1.55 ± 0.00 (2.7%)	2.07 ± 0.01 (2.0%)	3.08 ± 0.01 (1.3%)	4.09 ± 0.01 (1.3%)	5.12 ± 0.01 (1.6%)
ViewIT Catheter 2	0.5 mm/s	1.54 ± 0.01 (1.8%)	2.06 ± 0.01 (1.6%)	3.07 ± 0.01 (1.0%)	4.09 ± 0.01 (1.2%)	5.12 ± 0.01 (1.5%)
AltaView Catheter 1	0.5 mm/s	1.54 ± 0.00 (1.8%)	2.06 ± 0.01 (1.3%)	3.08 ± 0.01 (1.4%)	4.09 ± 0.00 (1.3%)	5.12 ± 0.01 (1.6%)
AltaView Catheter 1	3 mm/s	1.51 ± 0.01 (0.3%)	2.05 ± 0.01 (1.0%)	3.08 ± 0.02 (1.5%)	4.10 ± 0.01 (1.6%)	5.12 ± 0.01 (1.6%)
AltaView Catheter 1	9 mm/s	1.52 ± 0.01 (0.6%)	2.06 ± 0.01 (1.3%)	3.08 ± 0.01 (1.4%)	4.10 ± 0.01 (1.5%)	5.13 ± 0.01 (1.8%)
AltaView Catheter 2	0.5 mm/s	1.54 ± 0.01 (2.0%)	2.07 ± 0.01 (1.7%)	3.09 ± 0.01 (1.5%)	4.12 ± 0.02 (1.9%)	5.12 ± 0.01 (1.7%)
AltaView Catheter 2	3 mm/s	1.55 ± 0.00 (2.8%)	2.09 ± 0.01 (2.9%)	3.11 ± 0.01 (2.3%)	4.13 ± 0.01 (2.2%)	5.14 ± 0.01 (1.9%)
AltaView Catheter 2	9 mm/s	1.55 ± 0.01 (2.8%)	2.09 ± 0.01 (3.0%)	3.11 ± 0.01 (2.2%)	4.11 ± 0.01 (1.8%)	5.14 ± 0.01 (2.0%)
DualPro Catheter 1	0.5 mm/s	NA	NA	3.16 ± 0.02 (4.1%)	4.18 ± 0.01 (3.3%)	5.22 ± 0.00 (3.5%)
DualPro Catheter 2	0.5 mm/s	NA	NA	3.14 ± 0.01 (3.2%)	4.16 ± 0.01 (2.9%)	5.18 ± 0.01 (2.8%)
Refinity	0.5 mm/s	NA	NA	2.95 ± 0.01 (-2.9%)	3.96 ± 0.01 (-1.9%)	4.96 ± 0.01 (-1.6%)

Values are mean average lumen diameters ± standard deviation (relative difference in lumen diameter between measurement and actual phantom diameter). IVUS indicates intravascular ultrasound.

and precision of quantitative measures in all the imaging systems. Each imaging system has its specific calibration setting which can vary between imaging systems. Theoretically, the differences of lumen measurements between the employed imaging systems should be predominantly derived from difference in their calibration setting in the ideal environment in vitro. In fact, there were

slight quantitative differences between the IVUS vs FD-OCT / OFDI, and, of note, even between IVUS systems. Nonetheless, the differences in the quantitative measurements between the intracoronary imaging systems were small (mean ± standard deviation of 0.04 ± 0.05 mm, ranging from -0.09 to 0.14 mm) and the relative differences were less than 10% among the phantom models of

Table 2
Lumen diameter measured by OFDI and FD-OCT.

OCT/OFDI	Phantom Diameter				
	1.51 mm	2.03 mm	3.04 mm	4.04 mm	5.04 mm
FastView Catheter1, Contrast	1.52 ± 0.00 (0.9%)	2.08 ± 0.00 (2.4%)	3.05 ± 0.02 (0.5%)	4.10 ± 0.01 (1.5%)	5.11 ± 0.01 (1.4%)
FastView Catheter 1, Mixture	1.49 ± 0.01 (-1.2%)	2.04 ± 0.01 (0.5%)	3.07 ± 0.02 (1.0%)	4.12 ± 0.01 (1.9%)	5.10 ± 0.04 (1.1%)
FastView Catheter 1, Saline	1.53 ± 0.01 (1.0%)	2.03 ± 0.02 (0.1%)	3.04 ± 0.01 (0.0%)	4.10 ± 0.01 (1.6%)	5.12 ± 0.01 (1.5%)
FastView Catheter 2, Contrast	1.49 ± 0.01 (-1.2%)	2.08 ± 0.01 (2.4%)	3.08 ± 0.02 (1.3%)	4.09 ± 0.01 (1.2%)	5.10 ± 0.01 (1.3%)
FastView Catheter 2, Mixture	1.52 ± 0.01 (0.6%)	2.04 ± 0.03 (0.5%)	3.09 ± 0.02 (1.7%)	4.10 ± 0.01 (1.4%)	5.10 ± 0.01 (1.2%)
FastView Catheter 2, Saline	1.51 ± 0.00 (0.1%)	2.06 ± 0.01 (1.4%)	3.07 ± 0.01 (1.0%)	4.04 ± 0.01 (0.0%)	5.07 ± 0.02 (0.6%)
DragonFly Catheter 1, Contrast	1.48 ± 0.00 (-2.1%)	2.02 ± 0.00 (-0.3%)	3.05 ± 0.01 (0.2%)	4.06 ± 0.01 (0.4%)	5.07 ± 0.01 (0.6%)
DragonFly Catheter 1, Mixture	1.47 ± 0.00 (-2.6%)	2.01 ± 0.00 (-0.9%)	3.05 ± 0.01 (0.2%)	4.06 ± 0.00 (0.8%)	5.07 ± 0.01 (0.5%)
DragonFly Catheter 1, Saline	1.48 ± 0.00 (-2.1%)	2.02 ± 0.00 (-0.3%)	3.06 ± 0.01 (0.5%)	4.07 ± 0.01 (0.8%)	5.10 ± 0.03 (1.2%)
DragonFly Catheter 2, Contrast	1.48 ± 0.00 (-2.0%)	2.02 ± 0.01 (-0.6%)	3.03 ± 0.01 (-0.2%)	4.03 ± 0.01 (-0.3%)	5.04 ± 0.00 (0.0%)
DragonFly Catheter 2, Mixture	1.47 ± 0.01 (-2.6%)	2.00 ± 0.01 (-1.3%)	3.02 ± 0.01 (-0.5%)	4.03 ± 0.00 (-0.3%)	5.02 ± 0.01 (-0.4%)
DragonFly Catheter 2, Saline	1.47 ± 0.01 (-2.5%)	2.01 ± 0.01 (-0.8%)	3.03 ± 0.01 (-0.3%)	4.03 ± 0.01 (-0.2%)	5.04 ± 0.01 (0.1%)

Values are mean average lumen diameters ± standard deviation (relative difference in lumen diameter between measurement and actual phantom diameter). FD-OCT indicates frequency domain optical coherence tomography; Mixture, contrast-saline mixture (1:1 ratio); OFDI, optical frequency domain imaging.

Table 3
Lumen diameter measured by IVUS imaging systems after adjustment for the difference in speed of sound in saline and blood.

IVUS	Pullback	Phantom Diameter				
		1.51 mm	2.03 mm	3.04 mm	4.04 mm	5.04 mm
OptiCross Catheter 1	0.5 mm/s	1.54 ± 0.02 (2.1%)	2.09 ± 0.02 (2.9%)	3.09 ± 0.01 (1.6%)	4.05 ± 0.01 (0.2%)	5.06 ± 0.01 (0.5%)
OptiCross Catheter 2	0.5 mm/s	1.58 ± 0.01 (5.0%)	2.11 ± 0.02 (4.1%)	3.11 ± 0.01 (2.3%)	4.09 ± 0.01 (1.3%)	5.07 ± 0.01 (0.5%)
OptiCrossHD Catheter 1	0.5 mm/s	1.56 ± 0.01 (3.6%)	2.07 ± 0.02 (2.1%)	3.06 ± 0.00 (0.8%)	4.03 ± 0.01 (-0.2%)	5.03 ± 0.01 (-0.1%)
OptiCrossHD Catheter 2	0.5 mm/s	1.61 ± 0.01 (6.8%)	2.14 ± 0.02 (5.4%)	3.11 ± 0.01 (2.2%)	4.08 ± 0.01 (1.1%)	5.08 ± 0.00 (0.8%)
ViewIT Catheter 1	0.5 mm/s	1.53 ± 0.00 (1.5%)	2.04 ± 0.01 (0.5%)	3.02 ± 0.01 (-0.5%)	4.01 ± 0.01 (-0.8%)	5.01 ± 0.01 (-0.5%)
ViewIT Catheter 2	0.5 mm/s	1.52 ± 0.01 (0.7%)	2.03 ± 0.01 (0.1%)	3.02 ± 0.01 (-0.8%)	4.01 ± 0.01 (-0.8%)	5.01 ± 0.01 (-0.6%)
AltaView Catheter 1	0.5 mm/s	1.52 ± 0.00 (0.7%)	2.03 ± 0.01 (-0.2%)	3.02 ± 0.01 (-0.5%)	4.01 ± 0.00 (-0.8%)	5.01 ± 0.01 (-0.6%)
AltaView Catheter 1	3 mm/s	1.50 ± 0.01 (-0.8%)	2.02 ± 0.01 (-0.5%)	3.03 ± 0.01 (-0.4%)	4.02 ± 0.01 (-0.5%)	5.01 ± 0.01 (-0.5%)
AltaView Catheter 1	9 mm/s	1.50 ± 0.01 (-0.5%)	2.02 ± 0.01 (-0.2%)	3.03 ± 0.01 (-0.5%)	4.02 ± 0.01 (-0.6%)	5.02 ± 0.01 (-0.3%)
AltaView Catheter 2	0.5 mm/s	1.52 ± 0.01 (0.8%)	2.03 ± 0.01 (0.2%)	3.03 ± 0.01 (-0.4%)	4.03 ± 0.02 (-0.2%)	5.01 ± 0.01 (-0.5%)
AltaView Catheter 2	3 mm/s	1.54 ± 0.00 (1.7%)	2.06 ± 0.01 (1.4%)	3.05 ± 0.01 (0.4%)	4.04 ± 0.01 (0.1%)	5.03 ± 0.01 (-0.3%)
AltaView Catheter 2	9 mm/s	1.54 ± 0.01 (1.7%)	2.06 ± 0.01 (1.5%)	3.05 ± 0.01 (0.3%)	4.03 ± 0.01 (-0.3%)	5.03 ± 0.01 (-0.2%)
DualPro Catheter 1	0.5 mm/s	NA	NA	3.11 ± 0.02 (2.4%)	4.10 ± 0.01 (1.5%)	5.12 ± 0.00 (1.5%)
DualPro Catheter 2	0.5 mm/s	NA	NA	3.09 ± 0.01 (1.5%)	4.08 ± 0.01 (1.1%)	5.08 ± 0.01 (0.8%)
Refinity	0.5 mm/s	NA	NA	2.90 ± 0.01 (-4.5%)	3.89 ± 0.01 (-3.7%)	4.86 ± 0.01 (-3.5%)

2.03 mm or larger diameter. These are seemingly within the clinically acceptable range when performing cardiac catheterization procedures.

The present study has important limitations. The imaging procedures were performed under standardized conditions in the tank filled saline, contrast, or their mixture maintained at 37°C to avoid possible variability caused by varying blood characteristic. How-

ever, multiple factors in vivo affect the accuracy of quantitative measurements between IVUS and OCT /OFDI in the clinical settings. The phantom diameters measured by IVUS in saline can differ from those measured in blood as the speed of sound are theoretically different between in saline and in blood. In addition, we did not compare the accuracy of longitudinal length, area and volume measurements. Those need to be further investigated.

5. Conclusion

In conclusion, the present study demonstrated that contemporary intravascular imaging systems including OFDI, FD-OCT, and IVUS provided clinically acceptable accuracy and excellent precision of quantitative lumen measurement in phantom models in vitro across a wide range of dimensions. Future research to confirm these findings in vivo are warranted.

These authors take responsibility for all aspects of the reliability and freedom from bias of the data presented and their discussed interpretation.

Disclosure

Yoshio Kobayashi has received research grants from Abbott, Nipro, and Terumo. The other authors have reported that they have no relationships relevant to the contents of this paper to disclose.

Declaration of Competing Interest

The authors report no relationships that could be construed as a conflict of interest.

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