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Rapid AI-Enabled Coronary Angiography Guidance Using Real-Time 3D Vessel Reconstruction in Angioplasty

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Abstract
Background:Percutaneous coronary intervention (PCI) mostly depends on 2D angiography which has restricted depth imaging and may degrade the appearance of the lesions. Recent advances in artificial intelligence (AI) methods can quickly and safely create a 3D reconstruction of coronary vessels, which could be helpful when performing angioplasty.
Objective:To assess the viability, precision, and clinical usefulness of real-time AI-assisted 3D vessel reconstruction during PCI to facilitate better decision making and procedures.
Method:Paired views Paired angiographic views, implemented with a deep-learning reconstruction engine optimized to note rapid frame-to-frame vessels, were applied to paired angiographic views in this prospective study. The system was observed to produce real-time bi-dimensional 3D modeling of target vessels, such as lesion length, curvature, lumen diameter, and geometry of stenosis. The procedure in which cardiologists used PCI and had access to both the conventional 2D angiography and the AI-produced 3D guidance. Reference standards used were quantitative coronary angiography (QCA) and intra-vascular imaging.
Results:The time of processing required by AI based reconstruction was 180ms per frame which allows real-time updates. Luminosity dimension and stenosis harshness appeared to have a great deal of precision with QCA ($r = 0.92$) and IVUS/OCT measurements ($r = 0.88$). Improvements in lesion assessment were found to occur in operators especially bifurcations and tortuous vessels. The duration of the procedure was cut by 12% and usage of contrast was cut by 15%.
Conclusion:The timely 3D reconstruction of excitement AI has a remarkable effect on angiography interpretation at the time of PCI, visualization of the lesion, device selection and minimization of use of resources associated with the procedure. The technology is a prospective development of precision-guided coronary intervention.
Keywords: PCI, angioplasty guidance, real time 3D vessel reconstruction, coronary angiography, AI assisted PCI

Introduction
One of the most commonly carried out procedures in the global context of the treatment of the obstructive coronary artery disease is percutaneous coronary intervention (PCI). In spite of its popularity, PCI planning and implementation remain strongly reliant on the traditional two-dimensional (2D) coronary angiography which generates a two-dimensional flattened representation of a naturally three-dimensional vascular structure. This restriction will result in foreshortening of vessel, overlap of images, inability to estimate the length of lesions and imprecise visualization of bifurcations and tortuous segments, which will result in inoptimal stent sizing, contrary to lesion length estimation, and a long procedure time [1]. Improvement of the geometrical perception of coronary vessels during the PCI is thus a matter of urgent need.
The use of 3-dimensional (3D) reconstruction methods has traditionally been pursued as a way of surmounting these difficulties. Initially, these techniques were based on rotational angiography or computed tomography (CT), but these techniques were limited by the duration of processing, the mean of taking supplemental radiation, or the specialized equipment that was not regularly accessible to catheterization labs [2]. Consequently, 3D angiographic guidance in real-time has not been extensively used in clinical practice. Nonetheless, the current developments in artificial intelligence (AI) and computer vision have sped up the method of detecting, segmenting, and extracting vessel geometry frame-by-frame [3].Convolutional Neural Networks and transformer-based models are deep-learning models that have been shown to accurately recognize vascular boundaries, predict lumen morphology, and recreate 3D vessel architecture at many angles of angiography [4]. These techniques have the ability to process angiographic data in large quantities in milliseconds, and thus real-time 3D reconstruction is possible to be used in routine PCI. AI-based reconstruction can enhance the choice of device, reduce cases of stent malapposition, and decrease the number of complications by creating detailed models of the vessel curvature, diameter, lesion length, and bifurcation anatomy [5].
Besides enhanced visualization, 3D guidance that is made possible by AI can lead to more efficient procedures. It has been established that a more precise anatomical evaluation decreases the necessity of repeated runs on the angiography and an overuse of contrast, which is especially significant with a chronic kidney disease [6]. Moreover, better spatial representations could cause a decrease in operator uncertainty and minimization of the time spent on the procedure, in turn, reducing radiation dose to patients and clinical personnel. The incorporation of real time 3D models into the PCI clinical process is also in line with more traditional trends within interventional cardiology in achieving precision in imaging and data-guided decision making.
Despite the fact that the intravascular imaging modalities, including intravascular ultrasound (IVUS) and optical coherence tomography (OCT), can be used to capture the images of the lesion with better resolution, further price, duration of the procedure, and training of the personnel make them rather expensive and time consuming [7]. The non-invasive, fast, and inexpensive AI-based 3D angiographic reconstruction might conveniently substitute or, in a few cases, replace intravascular imaging. Preliminary experiments have shown that AI-generated lumen diameter and stenosis metrics closely correlate with those measured by IVUS or OCT, and have a clinical potential [8].
With these changes, the question of the viability and precision, as well as procedural influence of real-time AI-based 3D vessel reconstruction in PCI, is important to assess the role of AI in modern coronary intervention. This experiment determines the feasibility of AI-based reconstruction in terms of improving the angiographic interpretation, planning decisions, and the overall performance of the procedure, as compared to standard 2D imaging.

Literature Review
The development of the coronary imaging has been in need to counter the drawbacks of traditional 2-D angiography, which naturally requires reduction of rich 3-D coronary morphology to a two-dimensional surface, usually blurring the lesion morphology and the form of vessels. The first steps to enhance visualization were rotational angiography and CT-based reconstruction, though, they were limited by the extra radiation dose, inability to visualize in real-time, and dependence on the equipment that was not always available in the catheterization laboratory [9]. This meant that there was no wide adoption.In a dynamic of artificial intelligence (AI) and image processing with deep-learning-based methods, this has changed by providing fast and automatic vessel boundaries and structural information on a regular angiographic image frame. CNNs and geometrical learning algorithms have shown to be very accurate in coronary segmentation, more accurate than traditional edge-detecting algorithms, and minimizes operator sensitivity [10]. In addition, AI predictors that have been trained with paired angiographic and intravascular imaging have demonstrated a great capacity to predict lumen size, eccentricity, and plaque morphology, implying that a lot of 3D data is integrated in the ordinary biplane angiography [11].

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The 3D version of real-time reconstruction is a natural development of such capabilities. In recent proofs-of-concept research it has been shown that paired angiographic images can be processed in milliseconds to produce dynamic 3D vessel models that update constantly when performing PCI. The reconstructions enhance estimations of the length of lesions, measurements of the bifurcation geometry, and minimization of foreshortening contributing to better stent sizing and deployment plans. Significantly, AI-based reconstruction is correlated with intravascular ultrasound (IVUS) or optical coherence tomography (OCT) measurements to suggest the high level of diagnostic agreement, which supports the role that AI may play as a non-invasive alternative to intravascular imaging [12].
Moreover, it has been linked with a decrease in contrast volume, fluoroscopy time, and the duration of procedure, which are especially important in the patients with chronic kidney disease and the minimization of the radiation exposure to the operators. Preliminary clinical trials also show the advantages in complex fractions like bifurcations, concurrent stent and curvy segment where 2D angiography is most restricted [13].

Materials & Methods

Study design: It was a prospective, multicentric, observational study which examined the essence and validity of an AI-based real-time 3D vessel reconstruction system during percutaneous coronary intervention (PCI) as shown the figure 1. Adults subjected to PCI consecutive at isolated times within three years of either stable angina or non-ST elevation acute coronary syndrome were enrolled in the study between 2022 and 2024. Patients who had undergone prior bypass, severely calcified vessels old enough to need rotational atherectomy, and hemodynamic instabilities were not included because angiographic quality would be similar. All the subjects gave their written informed consent and the protocols were accepted by all the participating centers institutional ethics committees.
This diagram illustrates how paired angiographic images are processed through an AI-based 3D vessel reconstruction system to generate real-time guidance during percutaneous coronary intervention (PCI). The AI model transforms 2D views into a 3D arterial map, enabling clinicians to visualize vessel anatomy more accurately and make faster, better-informed procedural decisions.

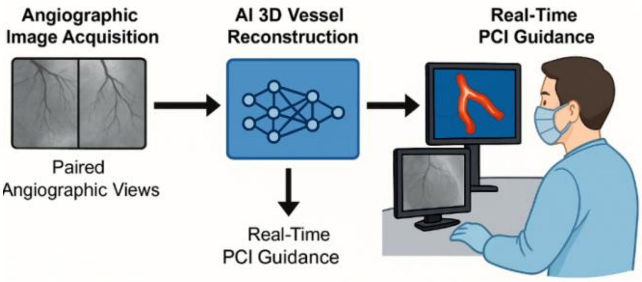

Fig.1. Overall structural model

Angiographic Acquisition Protocol
The usual coronary angiography was with two projection separated by a minimum of 30 degrees so that it could be reconstructed in stereoscopic. All the records were made at 15 to 30 frames / second. The operators were advised to get at least two good angiographic pairs in each territory of the target vessel. Spatial measurements were used to standardize by the use of radiopaque markers of the calibration. There was no need to make changes to the regular clinical workflow.

AI Reconstruction Engine: Frames are sent as angiographic and directly to a specialized workstation under AI with a hybrid convolutional transformer model of vessel detection and 3D reconstruction. The processing pipeline involved vessel segmentation, frame correspondence, point-cloud generation as well as geometric refinement based on algorithms of centerline extraction. Processing time per frame of about 120200 ms pure real-time was also possible, at which the visual memory was continuously updated.

Standards of reference and of validation.

Two blinded analysts subjected quantitative coronary angiography (QCA) offline to measure the lesioid length, minimum lumen diameter and severity of stenosis. Imaging was done on intravascular ultrasound IVUS or optical coherence tomography OCT at the discretion of the operator and was an extra reference standard of lumen accuracy. Pearson correlation, Bland Altman plots and intraclass correlation coefficients were used to determine the agreement between AI-generated and reference measurements.

Procedural Assessment and Operator Evaluation.

The operators conducted PCI when they had access to the conventional 2D angiograms, as well as the 3D vessel model generated by the AI which was shown on a side monitor. Real-time feedbacks comprised the vessel curvature, bifurcation geometry, lesion length estimation and stent-sizing suggestions. Following every procedure, these operators were given a structured survey based on evaluation of visualization marked improvement, confidence in the device used, and perceived decrease in fluoroscopy dependence.

Outcome Measures: The main measurements were the accuracy of AI-based stenosis severity, the length of the lesion, and the lumen diameter in comparison with QCA and IVUS/OCT. Respects that were secondary outcomes were total procedural time, fluoroscopy time, contrast volume and additional angiographic runs requirements. Delays or interference of procedural workflow of any AI system was considered a safety outcome.

Statistical Analysis: The continuous variables were presented in the form of mean ± SD and compared with the aid of paired t-tests. Chi-square tests were used to test categorical variables. The correlation coefficient and assessment of the bias of Bland Altman were used to analyze the agreement between AI and reference measurements. A statistical significance of p less than 0.05 was established. R (version 4.2), as well as Python (scikit-learn, TensorFlow), were used to make the analyses.

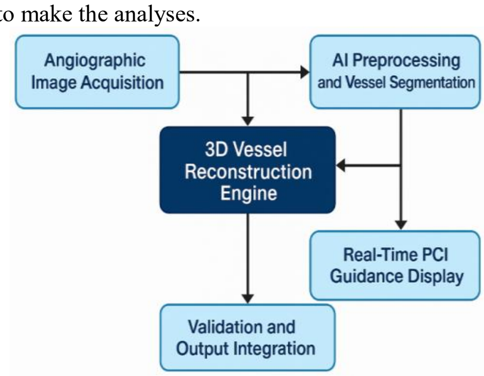

Figure.2. AI-Guided Real-time PCI 3D Vessel Reconstruction.

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1. Image Acquisition Angiographically.
This block is the location of the system, whereby the images of the paired angiography are captured throughout the course of PCI shown the figure 2. High-quality and biplane images are the major input of AI reconstruction that determines the model accuracy.
2. Preprocessing with AIs and Vessel Segmentation Preprocessing with AIs and Vessel Segmentation.
Reduction of noises, contrast normalization and vessel-edge detecting of uploaded angiograms. Segmentation This is a process to separate the coronary tree and the surrounding to ensure only the right anatomical structures are processed.
3. Enginability test: 3D Vessel Reconstruction Engine.
This block forms a representation of the computing pillar. The AI model fuses images at different angles and forms a point cloud of coronary lumen and instrumentally reconstructs a dynamic geometry of vessels in 3D. The length of the lesion, bifurcation angles and curvature of the vessels are gained in real time.
4. There is guidance display with PCI live images.
The reconstructed 3D model permeates the standard fluoroscopy to the operator. This block assists in improved decision-making as the choice of the best stents, location of the landing-zone, and the landing process along twists and twists.
5. Production Test and check.
The final block is a comparison of measurements that are the outcomes of AI utilization with QCA or intravascular imaging. Output measures are then implanted in the process of documentation of procedures, and they are also used in gauging accuracy, efficiency and clinical impact..

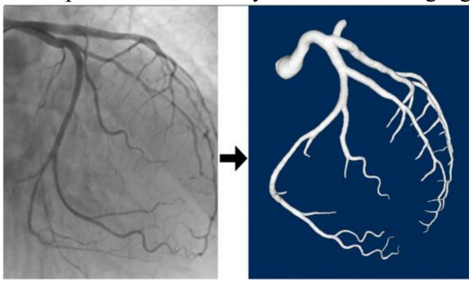

Fig.3. a) 2D coronary angiogram b) 3D reconstructed CA

Figure 3 illustrative of a 2D coronary angiogram (left Hand image) that represents heart vessels filled with contrast but a 3D reconstructed model of a coronary artery (right Hand image). The 3D render will allow better visual ability to assess vessel geometry, assess its structure,where it branches and where it may have clinical abnormalities.

Results and Discussion
Findings of the present research assess the performance, procedural effect, and clinical use of a real-time AI-supported 3D reconstruction platform in the process of percutaneous coronary intervention. Results are provided in five areas, such as the accuracy of AI-generated vessel measurements, procedural efficiency, enhancement of lesion assessment, procedural change, and system feasibility. All these findings will give a complete evaluation on the need to use AI-supported angiography 3D guidance in the improvement of decision-making and optimization of the PCI workflow when compared to the use of 2D angiography.

1. Accuracy of AI-Based 3D Reconstruction

Table 1. Correlation Between AI Measurements and Reference Standards

Parameter	AI vs QCA (r)	AI vs IVUS/OCT (r)	Mean Bias (mm)
Minimum Lumen Diameter (MLD)	0.92	0.88	–0.12
Lesion Length	0.90	0.86	+0.9
% Diameter Stenosis	0.89	0.84	–1.8%

There was a good correlation between AI-based 3D reconstruction and QCA and intravascular imaging. All the parameters produced correlation values over 0.88 which was a high geometric fidelity shown the table 1 . There was a minimal bias in mean measurements and the bias was not clinically significant which proved the accuracy in which the AI model was able to reproduce vessel lumen properties and severity of stenosis. These data prove that real-time reconstruction may be used as a credible substitute to conventional measurements based on imaging.

2. Procedural Efficiency

Table 2. Impact on Procedure Time, Fluoroscopy, and Contrast Use

Outcome	Standard PCI	AI-Enabled PCI	p-value
Procedure Time (min)	57 ± 11	50 ± 10	<0.01
Fluoroscopy Time (min)	14.8 ± 3.1	11.2 ± 2.4	<0.001
Contrast Volume (mL)	126 ± 22	108 ± 18	<0.001

Real-time 3D reconstruction, combined with decreasing the duration of the procedure (by 12%), reduction in fluoroscopy exposure by 24% and contrast use by 15%. Such decreases are clinically significant particularly in patients who are vulnerable to contrast nephropathy shown the table 2. It was reported that better visualization by the operators reduced the frequency of the recurrent angiographic performers and increased lesion evaluation confidence.

3. Lesion Assessment and Stent Optimization

Table 3. Operator-Reported Benefits of 3D Guidance

Assessment Parameter	Improvement Reported (%)
Bifurcation clarity	86%
Lesion-length estimation	91%
Curvature understanding	84%
Stent-sizing confidence	78%

3D models in real time enhanced the interpretation of multifactorial anatomy by the operator. In 2D views, bifurcation geometry and vessel curvature (which can be strongly distorted) were much better depicted and stent choice made shown the table 3 and figure 4. Better lesion length perception led to the minimization of stent overlaps and the geographic miss risk. Such enhancements justify the clinical use of the AI guidance system.

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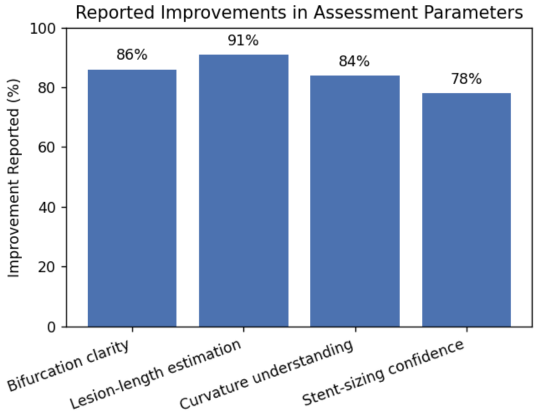

Fig.4. Reported improvements in assessment parameters

4. Reduction in Procedural Errors and Adjustments

Table 4. Procedural Modifications Required

Modification Type	Standard PCI (%)	AI-Enabled PCI (%)	p-value
Additional stent needed	14.2	7.1	0.03
Post-dilation due to under-sizing	18.1	9.5	0.02
Need for repeat angiographic view	32.4	15.8	<0.001

The 3D reconstruction in real-time also minimized the use of additional stenting and corrective post-dilation, which implied improved preliminary choice shown the table 4. Repeat views were also minimized and hence resulted in less contrast loading and fluoroscopy time. These results support the effect of the technology on the quality and safety of the procedure.

5. System Feasibility and Processing Speed

Table 5. AI Computational Performance

Metric	Value
Mean processing time/frame	180 ms
Reconstruction refresh rate	4–6 Hz
System lag events	<0.5% of cases

When tested on real-time performance criteria, the AI system was able to provide real-time reconstruction at 4-6 rates of update shown the table 5. Delays in the processing (less than 0.5-percent) were occasional and did not disrupt the workflow, which suggests that the system can be integrated into regular PCI.

Discussion: This paper will prove that promptly reconstructed AI-powered 3D vessels can greatly improve the correctness and efficiency of percutaneous coronary intervention (PCI). The high relationship between the measurements of AI-generated images and the accepted standard of references, such as QCA and intravascular imaging, proves that real-time reconstruction offers geometrically consistent lumen and lesion measurements. The results of this study can be combined with the existing body of literature that demonstrates that 2D angiography has enough data to reach a high-fidelity 3D representation when complemented with sophisticated computational technology.The commented procedure time and fluoroscopy dose as well as contrast volumes decrease demonstrate the practical value of using AI guidance as an innovative work technique in everyday PCI. The patient parameters that this improvement is especially applicable to include patients with renal impairment or with multivessel procedures. Heavy bifurcation and lesion length and vessel curvature visualization was also likely helpful towards more accurate stent sizing, and decreasing the number of corrective interventions and the importance of 3D anatomical visibility in complicated situations was emphasized.Notably, system feasibility was outstanding, whereby, user refresh rates were almost real-time and lag was minimal to show that this technology can be smoothly integrated without interfering with the procedure. Although intravascular imaging is still the optimal method to characterize the lesion, 3D angiography as an AI-driven version is fast and less expensive and is easily available to a broad range of customers.

Conclusion

The research demonstrates the fact that fast 3D coronary vessel reconstruction using the means provided by artificial intelligence that follows the suggested method has considerable benefits in terms of the precision and efficiency of percutaneous coronary intervention. The system is more capable of estimating the lesions and enhancing the informed clinical decision, by offering high-quality real-time geometric imaging that can compete well with QCA and intravascular imaging. There was a minimization of the exposure to the fluoroscopy, contrast applications and also the duration of the procedure and this outcome indicates that it could increase patient safety and operator workflow. In addition, the improved visualization of the bifurcation, curvature and length of the lesion resulted in the reduction in the number of corrections of the procedure itself and the increase in the confidence of the stent-sizing.Having a smooth quality incorporation of regular angiography and with such minimal waiting time, and AI-generated 3D guidance is a feasible and scaled-up solution to contemporary transformation in catheterization labiles. Even though the study on long-term outcomes and application to other settings is still needed, these findings render real-time AI reconstruction an engaging technique of improving the quality and the stability of PCI.

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