RSNA 2023 Edition

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## Issue Highlights

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# Deep Learning-Based Reconstruction of Coronary CT Angiography in Patients with Diverse Anatomical and Pathological Complexities

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## 1. Introduction

The utility of Coronary Computed Tomography Angiography (CCTA) as a non-invasive diagnostic tool for coronary artery disease (CAD), particularly in terms of its high sensitivity and negative predictive value, has been widely acknowledged [1]. European and American guidelines advocate for its employment as a primary approach in managing stable chest pain, especially in patients with an intermediate pre-test probability of CAD [2, 3]. Over the last decade, the application of CCTA has experienced a substantial surge [4]. Furthermore, the usage has risen by 14% in the aftermath of the COVID-19 pandemic, compared to the pre-pandemic phase [5].

The analysis of coronary computed tomography angiography (CCTA) is a laborious and time-consuming task due to the necessary reconstruction of major epicardial vessels in multiple formats and the detailed assessment of coronary atherosclerosis. A previous survey found that the median time for post-processing and interpretation of CCTA images was 15 and 18 minutes, respectively [6]. Furthermore, the presence of complex coronary lesions, such as chronic total occlusion (CTO), anomalies in vessel origin, bypass grafts, stents, and severe calcification, further complicates and extends the process of reconstruction and interpretation. Consequently, with the increasing number of CCTA cases being performed, the conventional manual reconstruction significantly restricts the daily capacity for practicing CCTA [7].

Over the past decade, significant progress has been made in the field of deep learning (DL)-assisted medical image processing, particularly in tissue segmentation, lesion detection, and disease characterization [8]. Deep learning approaches have shown promising results in vessel segmentation, primarily due to their ability to learn automatically and generalize well. These approaches have been successfully applied to various types of medical images, including retinal vessel fundus images [9], head and neck angiograms [10, 11], and cardiac CT angiograms.

The objective of this study is to evaluate the effectiveness of a deep learning-based segmentation model in automatically reconstructing coronary vessels in different complex clinical situations. These scenarios include CTO, anomalies in coronary vessel origin, bypass grafts, and stents.

## 2. Materials and Methods

### 2.1 Patient Data Sets

All three distinct hospital's (comprising two tertiary - 1. Shanghai General Hospital, Shanghai, 2. Shanghai Jiao Tong University Affiliated Sixth People’s Hospital and one secondary institution - Shanghai General Hospital, Jiading Branch) ethics committee sanctioned this retrospective analysis, eliminating the need for informed consent. For our validation cohort, we amassed data on 1,023 patients who underwent CCTA across three distinct hospitals from January 2019 to June 2022. We excluded cases where CCTA image quality was severely compromised, specifically those with extreme artifacts that rendered the images non-diagnostic. To evaluate the effectiveness of reconstructing intricate coronary structures, our validation cohort included 211 chronic total occlusion patients with 240 CTO lesions, 105 with bypass grafts, 152 with stents, and 100 with origin anomalies, notably the anomalous origin of the coronary artery from the opposite sinus (ACAOS).

### 2.2 CCTA Image Acquisition

For the validation set, we included CCTA exams performed on six CT scanners from four vendors to validate the generalizability of developed model across varies CT equipment. These include: 1) third-generation dual source CT (SOMATOM Force, Siemens Healthineers); 2) 256-row wide detector CT scanner (Revolution, GE Healthcare); 3) 320-row wide detector CT scanner (uCT 960+, United Imaging); 4) dual-layer detector spectral CT (IQon, Philips Healthcare); 5) 64-row multidetector CT (Definition AS+, Siemens Healthineers); and 6) 64-row multidetector CT (uCT 760, United Imaging). Retrospective ECG-gating acquisition was used for 128-slice multidetector CT and dual-layer detector spectral CT whereas prospective ECG-triggering acquisition was adopted for third-generation dual source CT and wide detector CT with automatic tube voltage and dose modulation.

### 2.3 DL Model Development

In this work, the automated CCTA coronary reconstruction was performed using uAI® Discover CoronaryCTA® solution (United Imaging Intelligence Inc., Shanghai, China). It employs a progressive learning framework consisting of two main components as shown in Figure 1 [12]: (a) the Spatial Anatomical Dependency (SAD) module and (b) the Hierarchical Topology Learning (HTL) module. The SAD module aims to perform an initial segmentation of both the heart chambers and coronary arteries. The segmentation outcomes from this module are then used to compute distance field maps that represent the spatial relationship between the artery and the heart. Meanwhile, the HTL module is engineered to further refine the initial coronary segmentation. This refinement is achieved through the multi-level learning of coronary topological features, encompassing key points, centerlines, and adjacent cube-connectivity. The integration of these two modules substantially enhances the accuracy and consistency of segmenting coronary arteries, accounting for their varied shapes, dimensions, and spatial orientations in different individuals.

### 2.4 Efficacy of DL-assisted and conventional CCTA reconstruction

From each study, the cardiac phase image showing optimal image quality (with the least motion artifact) was manually selected and processed by both the Discover CoronaryCTA® software and default commercially available workstations provided by CT vendors. The procedures are hereinafter referred as DL-assisted reconstruction and conventional reconstruction, respectively. All CCTA exams were randomly assigned to two junior cardiovascular radiologists (with 4-year and 6-year experience in cardiovascular imaging) and two radiology residents (in the third year and fourth year of residency) for coronary reconstruction. In instances where the software was unable to automatically achieve a successful segmentation of the coronary vessels, manual corrections were made using the built-in editing functions.

Each exam underwent both DL-assisted and conventional reconstruction by the same person, ensuring a one-month interval between the two reconstructions to mitigate memory biases. An independent senior cardiovascular radiologist, with 14 years of expertise in cardiovascular imaging and unaware of the reconstruction techniques employed, assessed the quality of the reconstructions. The assessment utilized a 5-tier scale as follows:

4 = All vessels are flawlessly segmented, with no interruptions, venous interferences, or centerline deviations.

3 = Vessels are displayed without interruptions, venous interferences, or centerline deviations, yet minor distal branches of less than 1mm in diameter were omitted.

2 = Vessels are displayed with minor interruptions, venous interferences, or centerline deviations, or omitting distal branches of less than 1mm in diameter.

1 = Vessels are shown with moderate interruptions, venous contaminations, or centerline deviations, or branches ranging from 1mm to 1.5mm in diameter were excluded.

0 = Vessels have severe interruptions, venous contaminations, or centerline deviations, or branches measuring 1.5mm or more in diameter were not represented.

A reconstruction was considered successful in this work when the post-processing of the vessels reached scores of 3 or 4 on the aforementioned 5-point scale and are applied to native coronary vessels, chronic total occlusions, bypass grafts, coronary stents, and origin anomalies.

The clinical efficiency of the two methods was evaluated based on the total post-processing duration. This duration was demarcated as the span from the commencement of image loading to the successful completion of all necessary reconstructions, encompassing any requisite manual edits. For cases involving CTO, this post-processing timeframe also incorporated the assessment of parameters related to the J-CTO score, including total occlusion length, CTO calcification burden, stump morphology (either blunt or tapered), and the tortuosity of the course.

### 2.5 Statistics Analysis

Statistical analysis was performed using IBM SPSS Statistics 22.0 (IBM Corporation) and MedCalc Statistical Software

20.019 (MedCalc Software Ltd). Continuous variables are presented as mean ± SD if normally distributed or as median and interquartile range (IQR) otherwise. Normal distribution was assessed using the probability-probability plot. Ordinal categorical variables are presented as median and IQR. Categorical variables are presented as the number and percentage of patients. Paired Samples Wilcoxon signed ranks test was used to compare the difference of image quality and total processing time. Successful rate of DL-assisted reconstruction and conventional reconstruction was compared using the McNemar test. A two-tail $p < 0.05$ was considered statistically significant.

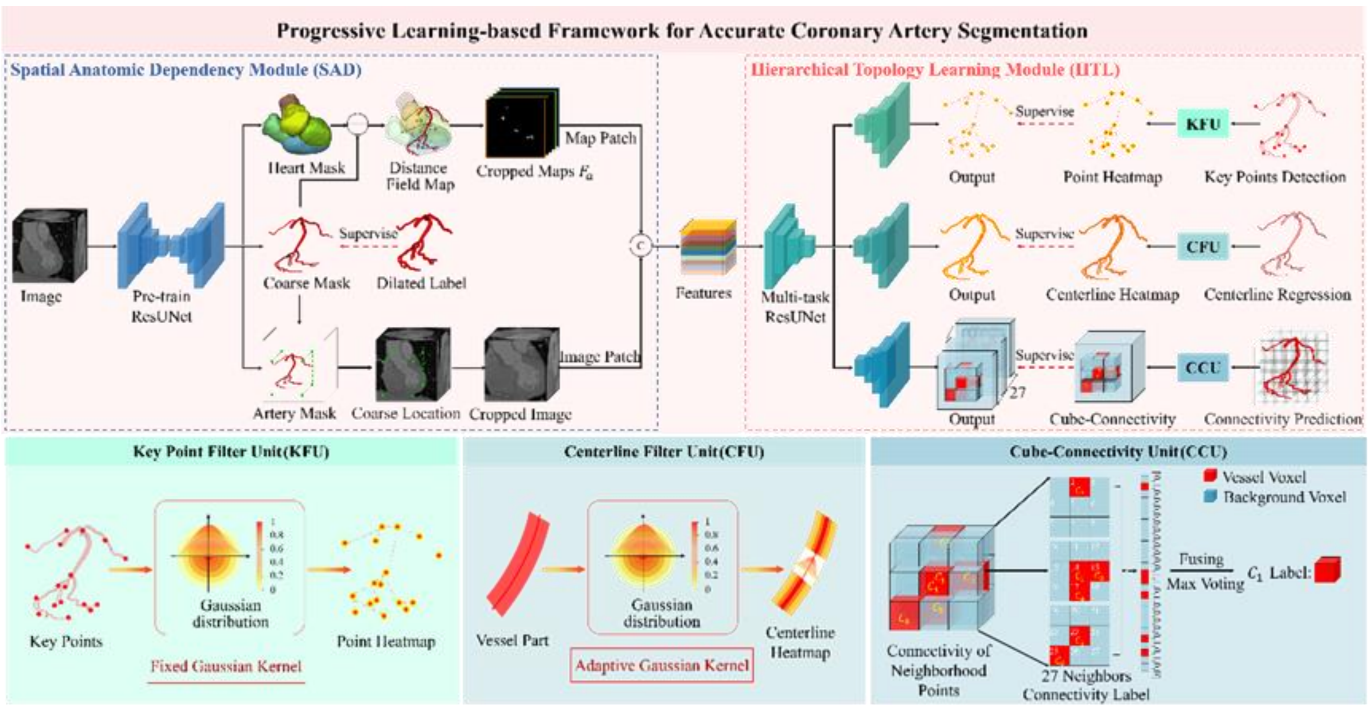


Figure 1. The progressive framework of the coronary segmentation model.

# 3. Results

## 3.1 Efficacy of DL-assisted reconstruction of CTOs

In the DL-assisted reconstruction, a remarkable 95% (228 out of 240) of CTO lesions were successfully segmented with no need for manual adjustments (see Figure 2). Of the 12 lesions necessitating manual intervention, 11 were amendable to further quantitative analysis following radiologist-led vessel editing. A single lesion remained uncorrectable. The primary factors prompting manual corrections for the DL model included the misidentification of contrast material–contaminated coronary veins as blocked arteries (five cases), the occlusion of diminutive vessels with diameters less than 2 mm (three cases), a tortuous trajectory (two cases), and mild artifact presence (two cases). By contrast, the traditional workstation automatically reconstructed occlusions in merely 48% (116 out of 240) of the lesions, markedly inferior to the DL-assisted method (P < .001). Predominant causes for manual revisions for the conventional workstation were extended occlusions with a length of 2 cm or more (57 cases), blockages in tiny vessels with diameters up to 2 mm (40 cases), mistaking contrast-contaminated veins for obstructed arteries (13 cases), sinuous pathways (12 cases), and minor artifact presence (two cases). The overall processing and evaluation duration utilizing the DL model was notably reduced compared to the standard manual method, with times recorded as 121 seconds ± 20 versus 456 seconds ± 68 for the junior radiologist (P < .001) and 106 seconds ± 14 versus 348 seconds ± 70 for the senior radiologist (P < .001).

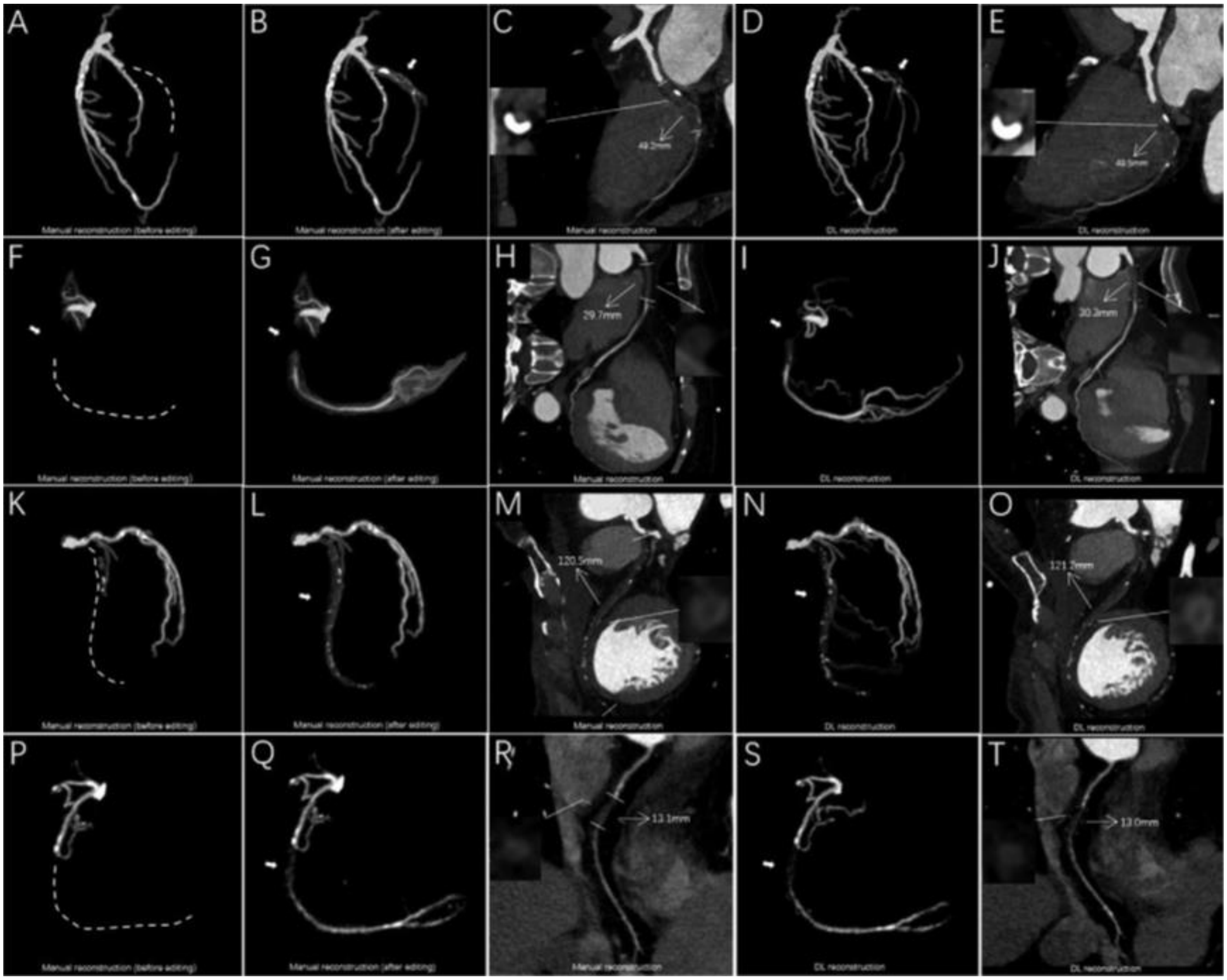


Figure 2. A comparison of example chronic total occlusion (CTO) lesion images utilizing DL-assisted reconstruction versus reconstruction with conventional workstations.

In a 49-year-old male with a CTO in the left circumflex artery, imaged with a third-generation dual-source CT scanner: (A) The standard workstation couldn't delineate the occluded segment (highlighted by dashed line). (B) Manual tracing of the CTO was conducted using the multiple-clicks vessel function (indicated by arrow), revealing a bend under 45°. (C) Conventional curved planar reformation (CPR) showed an occlusion length of 49.2 mm with a blunt termination. Calcium was found to constitute a minimum of 50% of the lumen area. Analysis duration: 423 seconds. (D) The DL model comprehensively identified the CTO trajectory, capturing several minor branches. (E) DL-based CPR displayed a CTO span of 49.5 mm, consistent calcium composition, and a reduced analysis time of 100 seconds.

In a 56-year-old female with a CTO in the right coronary artery (RCA), captured using a 128-section CT: (F-G) The standard platform struggled to identify both the occlusion and the distal lumen, later manually traced, indicating a CTO bend exceeding 45°. (H) Standard CPR illustrated an occlusion of 29.7 mm ending with a tapered stump, and no calcification. Analysis took 613 seconds. (I-J) In contrast, the DL model reconstructed the full CTO path and estimated its length at 30.3 mm in 105 seconds.

For a 74-year-old female with a CTO in the left anterior descending artery, using third-generation dual-source CT: (K-L) Initial extraction was unsuccessful for the occlusion and distal lumen. Post-manual tracing, the CTO bend was under 45°. (M) Traditional CPR depicted an extensive 120.5 mm CTO with a blunt end and no calcification, analyzed in 1077 seconds. (N-O) DL's efficacy was evident as it traced the complete CTO, estimating it at 121.2 mm in just 117 seconds.

For a 61-year-old female with an RCA CTO, analyzed with a 256-section wide detector CT: (P-Q) The conventional method missed the occlusion and distal lumen. After manual input, the CTO bend was seen to be under 45°. (R) Standard CPR indicated a 13.1 mm CTO with a blunt end and no calcification, taking 420 seconds. (S-T) The DL methodology precisely traced the CTO, gauging its length at 13 mm and concluding the process in 112 seconds.


Figure 3. Comparative display of DL-assisted versus conventional workstation reconstruction in patients exhibiting complex coronary anatomies.

### 3.2 Efficacy of DL-assisted reconstruction of native vessel, stents, bypass grafts, and origin anomaly

The DL-model demonstrated superior automatic segmentation capabilities when applied to intricate coronary anatomies, including stents, bypass grafts, and origin anomalies, as shown in Figure 3. Quantitative assessment revealed that the model consistently produced images of enhanced quality across all subgroup categories: stent (4 [IQR, 4 – 4] compared to 3 [IQR, 3 - 4]), bypass graft (4 [IQR, 3 – 4] versus 3 [IQR, 2 – 4]), and origin anomaly (4 [IQR, 4 – 4] in comparison to 4 [IQR, 3 – 4]), with all yielding p-values < .001 (Refer to Figure 4 for details). Moreover, a significant observation was the dominant presence of score 4 (indicating exemplary reconstruction image quality), which constituted 93.4%, 73.3%, and 91.0% of patients with stents, bypass grafts, and origin anomalies, respectively. In stark contrast, the conventional workstation reconstruction achieved this score in only 37.5%, 40.0%, and 52.0% of the cases, respectively, with all these instances presenting p-values < .001.

In most subgroups, the successful (score = 3 or 4) reconstruction rates by DL-model exceeded 97% except for the bypass graft (76.2%). The main reasons for failed reconstructions included inability to track the interarterial course of ACAOS (3 cases), occluded left internal mammary artery (LIMA) (9 cases) and saphenous venous graft (SVG) / radial artery graft (16 cases).

Panels A-H represent imaging from a 71-year-old male with a sequential SVG-LAD-OM-LCx-PDA graft captured using a third-generation dual-source CT scanner.

A-D are images reconstructed through the DL model, characterized by an image quality score of 4. The overall processing duration was 11 seconds, obviating the need for manual intervention. Specifically, A depicts volume rendering (VR), B showcases maximal intensity projection (MIP), C presents curved planar reformation (CPR), and D provides a cross-sectional perspective, delineating the full course of the patent graft.

E-H convey images rendered using traditional reconstruction techniques, also achieving an image quality score of 4. However, the processing time extended to 977 seconds. The illustrations are analogous in nature with E for VR, F for MIP, G for CPR, and H delineating the patent graft's full course.

Panels I-P present imaging from a 58-year-old female diagnosed with a subpulmonic anomalous origin of the LAD from the right coronary sinus, captured using a 64-row multidetector CT scanner.

I-L are reconstructions via the DL model, exhibiting an image quality score of 4, and processed in merely 7 seconds without manual modifications. The illustrations include I for VR, J for MIP, K for CPR, and L offering a comprehensive perspective of the anomalous LAD.

M-P highlight traditional reconstruction techniques, delivering an image quality score of 3, attributed to the omission of smaller distal branches (diameter <1mm). The process spanned 417 seconds. The sequence remains consistent with M for VR, N for MIP, O for CPR, and P displaying the anomalous LAD, albeit with fewer minuscule distal branches relative to the DL model reconstructions.

Panels Q-X detail imaging from a 68-year-old female with a stent in the first diagonal, obtained using a 256-row wide detector CT scanner.

Q-T employ the DL model for reconstruction, resulting in an image quality score of 4 and a rapid processing time of 17 seconds without manual adjustments. The sequence comprises Q for VR, R for MIP, S for CPR, and T vividly presenting the full course of the stented vessel.

U-X rely on traditional reconstruction, achieving an image quality score of 3. The process took 782 seconds. The series include U for VR, V for MIP, W for CPR, and X showing the stent, though lacking several smaller distal branches.

Relative to the conventional reconstruction, the median processing duration for DL-assisted reconstruction exhibited a substantial reduction, declining from 465.0 seconds (IQR, 337.5 – 656.0 seconds) to a mere 11.0 seconds (IQR, 8.0 – 31.0 seconds) across the patient cohort. This trend was consistently discernible in every subgroup, with each showing significant differences (P < .05) as depicted in Figure 5.

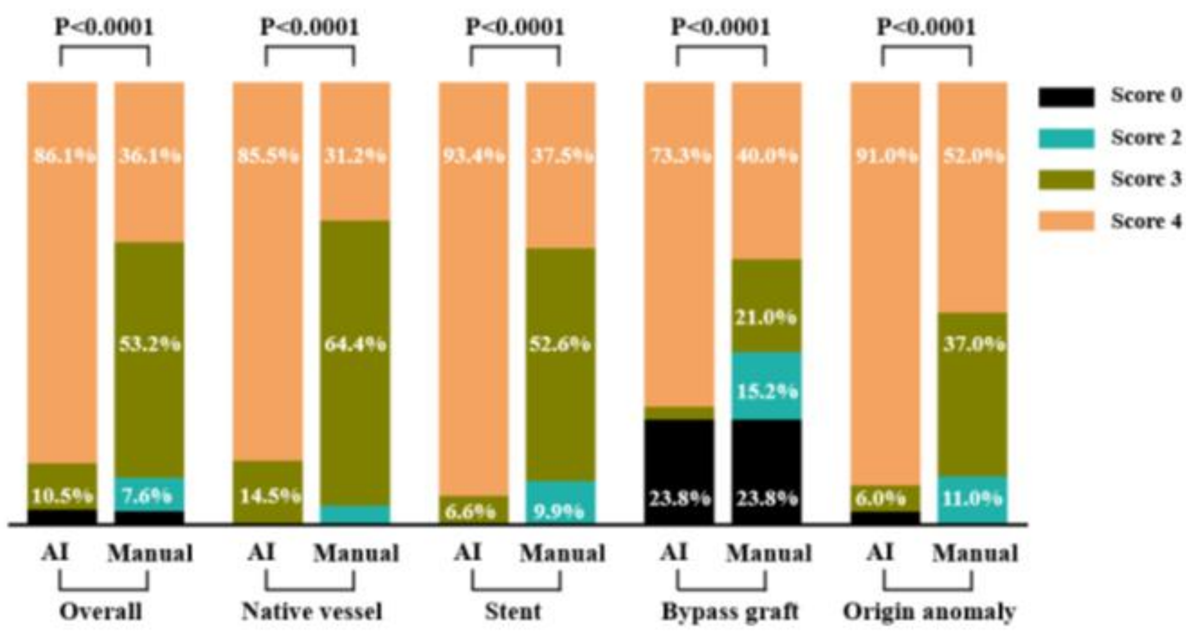


Figure 4. Comparative analysis of image quality between DL-assisted (AI) and conventional (Manual) reconstruction across diverse subgroups. Abbreviation: AI = Artificial Intelligence.

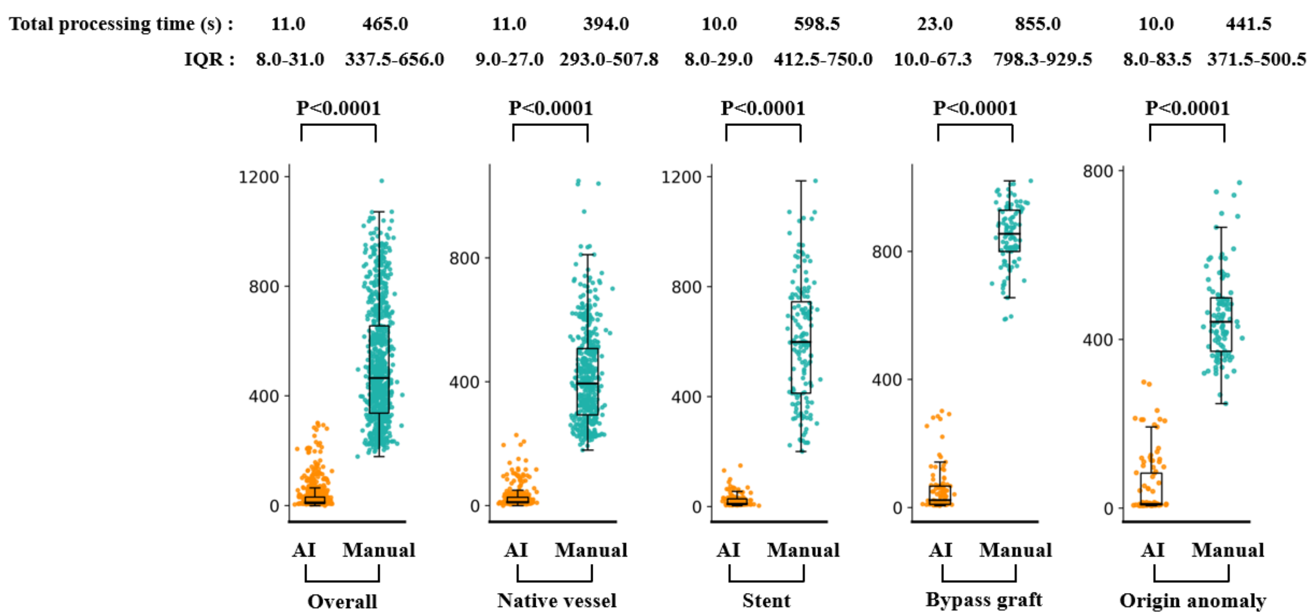


Figure 5. Comparative evaluation of total processing duration between DL-assisted (AI) and conventional (manual) reconstruction. The DL-assisted approach consistently yielded a markedly reduced processing time relative to the conventional method across all examined groups. Abbreviations: AI = Artificial Intelligence; IQR = Interquartile Range

## 4. Discussion

CCTA is a prevalent non-invasive imaging technique utilized in the clinical diagnosis of CAD. There has been a significant surge in the utilization of CCTA over recent decades, leading to an increased demand for post-processing. Contemporary research has explored the application of AI-driven models for the automated segmentation of CCTA, resulting in enhanced outcomes in native vessel reconstruction. Nonetheless, for patients presenting with anatomical and pathological intricacies, the automated reconstruction of coronary arteries continues to pose challenges due to inherent technical difficulties.

Coronary CTO constitutes one of the most challenging lesions to address during coronary intervention. CCTA stands out as an instrumental tool for guiding CTO revascularization, given its distinct capability to provide an in-depth anatomical assessment of occlusion features. Nonetheless, the automated reconstruction of occluded vessel segments and the connection of distal interrupted arteries present technical hurdles. Consequently, manual adjustments are frequently necessary on conventional workstations.

The present study strongly supports the use of DL-assisted reconstruction to facilitate CTO evaluation in clinical practice. The uAI® Discover CoronaryCTA® provides fully automated vessel segmentation and a variety of reconstruction formats (maximal intensity projection, volume rendering, curved planar reformats, etc.) without need for manual adjustments. This process typically concludes within 2 minutes, remarkably quicker than conventional workstations. It will specifically benefit interventional cardiologists, who are usually not as experienced as radiologists in terms of performing CCTA post-processing.

Coronary stent is another hard entity for automatic reconstruction, especially in terms of accurate centerline tracing in CPR images. As stent strut has high attenuation value, it may sometimes be misidentified as contrast-enhanced lumen and therefore leads to deviated centerlines in the stented segment, which usually requires manual adjustment. However, this study demonstrates that DL-assisted reconstruction was able to generate CPR images with accurate centerline tracing in all patients studied, with an impressive 93.4% attaining a score of 4. In contrast, conventional workstations only achieved this score for 37.5% of the patients. Consequently, DL-assisted CCTA post-processing appears to be a promising approach for patients with coronary stents.

As for origin anomalies, the inter-arterial type of ACAOS predominates in the present cohort. This presents a heightened technical challenge for automatic reconstruction due to the anomalous artery's ostium typically being situated at a considerable distance from its usual location, coupled with the artery's proximal course navigating between the pulmonary trunk and the ascending aorta. Notably, findings from this study revealed that DL-assisted reconstruction adeptly segmented the anomalous coronary artery in 97.0% of the subjects. This positions the DL methodology as highly suitable for automatic reconstruction, offering a substantial reduction in post-processing time compared to traditional workstation techniques.

Finally, coronary bypass graft is probably the utmost challenging scenario for automatic reconstruction of CCTA. This is chiefly attributed to the substantial variability in the count and trajectory of SVGs or radial arteries across various surgical interventions.

Within the scope of this research, the entire trajectory of LIMA was precisely identified for all patients. Similarly, non-occluded SVGs or radial grafts exhibited a 100% identification rate, regardless of procedural discrepancies. Yet, a notable limitation was the model's inability to detect ostially occluded grafts. The primary reason is the indiscernibility of a collapsed graft lumen in CCTA. In comparison to arterial blockages where a thrombosed lumen is still visible on CCTA, a collapsed venous graft often displays no evident residual lumen. Tracing such grafts remains a persistent challenge, impacting both traditional workstation-based methods and DL-assisted reconstruction techniques. The findings from this study reveal that both methods struggled to accurately map the course of occluded grafts.

Our study has several limitations. Initially, while the DL-assisted reconstruction facilitates automated delineation and reconstruction of the coronary vasculature with commendable precision and efficiency, the reliability of DL-driven lesion identification - pertaining to stenosis severity and plaque characterization - remains unverified. Furthermore, the present model struggles to track bypass grafts exhibiting proximal anastomosis occlusions. Consequently, there is a risk of neglecting obstructed grafts without meticulous manual oversight.

## 5. Conclusion

In conclusion, the DL-assisted uAI® Discover CoronaryCTA® solution facilitates a fully automated reconstruction of native coronary vessels, bypass grafts, stents, and origin anomalies, achieving both high precision and efficiency. Utilizing the DL model markedly reduces post-processing durations and enhances the CCTA post-processing workflow.

## 6. Image/Figure Courtesy

All images are the courtesy of three distinct hospital's comprising two tertiary - 1. Shanghai General Hospital, Shanghai, 2. Shanghai Jiao Tong University Affiliated Sixth

People's Hospital and one secondary institution - Shanghai General Hospital, Jiading Branch

## 7. References


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