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Automatic assessment of collaterals physiology in chronic total occlusions by means of artificial intelligence

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Abstract

Background: *Assessment of collaterals physiology in chronic total occlusions (CTO) currently requires dedicated devices, adds complexity, and increases the cost of the intervention. This study sought to derive collaterals physiology from flow velocity changes (ΔV) in donor arteries, calculated with artificial intelligence-aided angiography.*

Methods: *Angiographies with successful percutaneous coronary intervention (PCI) in 2 centers were retrospectively analyzed. CTO collaterals were angiographically evaluated according to Rentrop and collateral connections (CC) classifications. Flow velocities in the primary and secondary collateral donor arteries (PCDA, SCDA) were automatically computed pre and post PCI, based on a novel deep-learning model to extract the length/time curve of the coronary filling in angiography. Parameters of collaterals physiology, Δcollateral-flow ($\Delta\phi_{coll}$) and Δcollateral-flow-index (ΔCFI), were derived from the ΔV pre-post.*

Results: *The analysis was feasible in 105 out of 130 patients. Flow velocity in the PCDA significantly decreased after CTO-PCI, proportionally to the angiographic collateral grading (Rentrop 1: 0.02 ± 0.01 m/s; Rentrop 2: 0.04 ± 0.01 m/s; Rentrop 3: 0.07 ± 0.02 m/s; $p < 0.001$; CC0: 0.01 ± 0.01 m/s; CC1: 0.04 ± ± 0.02 m/s; CC2: 0.06 ± 0.02 m/s; $p < 0.001$). $\Delta\phi_{coll}$ and ΔCFI paralleled ΔV. SCDA also showed a greater reduction in flow velocity if its collateral channels were CC1 vs. CC0 (0.03 ± 0.01 vs. 0.01 ± 0.01 m/s; $p < 0.001$). For each individual patient, ΔV was more pronounced in the PCDA than in the SCDA.*

Conclusions: *Automatic assessment of collaterals physiology in CTO is feasible, based on a deep-learning model analyzing the filling of the donor vessels in angiography. The changes in collateral flow with this novel method are quantitatively proportional to the angiographic grading of the collaterals.*
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Key words: chronic total occlusion, coronary collateral circulation, deep learning, collateral donor artery, intracoronary physiology

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Introduction

Coronary chronic total occlusion (CTO) is found in approximately 20% of patients referred for diagnostic coronary angiography [1]. Percutaneous coronary intervention (PCI) can significantly relieve ischemia, improving clinical symptoms and quality of life [2–5]. In most patients with CTO, the viability of the subtended myocardium is preserved by coronary collaterals [6–9], whose careful evaluation is of critical importance for an adequate planning of the revascularization strategy [10, 11]. In routine clinical practice, this evaluation relies exclusively on angiography, namely on Rentrop classification [12] and collateral connections (CC) grading [10], while detailed physiologic assessment of collaterals is often circumvented because it is time consuming and requires the exchange of dedicated wires and devices that prolong the duration and increase the complexity and expenditure of an intervention.

The current study describes a novel, fully--automatic method of physiologic assessment of CTO collaterals, based on a previously validated deep-learning model of coronary segmentation in angiography [13], which can be implemented in standard coronary angiography without altering the standard operational workflow of the CTO intervention, and explores its consistency with standard angiographic classifications of collaterals.

Methods

Study population

This was a retrospective multicenter study that aimed to automatically calculate the collaterals flow (Φ_{coll}) and the collateral flow index (CFI) from each donor artery in CTO patients and explore its association with standard angiographic classifications of collaterals [10, 12]. Patients undergoing PCI of a CTO at Ruijin Hospital (Shanghai Jiao Tong University School of Medicine, Shanghai, CN) and Guangdong Provincial People's Hospital (Guangdong, CN) between December 2016 and January 2021 were screened. Major inclusion criteria were as follows: 1) single-vessel CTO with an indication for revascularization; 2) presence of collateral filling (Rentrop > 0) [12]; 3) technical success in CTO percutaneous recanalization exclusively achieved by antegrade approach [14]; and 4) appropriate angiographic projections of CTO and donor arteries before and after successful CTO intervention, defined as those providing maximal straightening of the target vessel, while minimizing foreshortening and vessel overlap. Exclusion criteria were as follows: 1) poor angiography quality for luminal edge detection; 2) excessive overlap or foreshortening; 3) presence of intracoronary devices (e.g., wires, microcatheters, etc.) during the acquisition of the angiographies required for the analysis; 4) previous coronary bypass grafting; and 5) collateral crossing with a microcatheter, balloon, or similar device at some point of the intervention.

Coronary CTO was defined as a 100% stenosis in angiography, with Thrombolysis in Myocardial Infarction (TIMI) grade 0 flow for ≥ 3 months [1, 14]. Estimation of occlusion duration was based on clinical symptoms, history of myocardial infarction in the target vessel territory, or previous angiogram [1]. Coronary angiography and CTO intervention were performed via radial or femoral approach with 6–8 F guiding catheters, bilateral contrast injection, and standard current CTO techniques, according to the principles of the hybrid approach [1, 2, 15]. For the purposes of the study, successful CTO recanalization was defined as technical success, i.e., achievement of TIMI grade 2 or greater antegrade flow in all ≥ 2.5-mm distal branches with < 30% residual stenosis of the target CTO lesion at procedure end [14].

The study complied with the principles of good clinical practice and with the Declaration of Helsinki for investigation in human beings. The study protocol was approved by the corresponding institutional review boards. All patients signed an informed consent form to retrospectively share and use their clinical data for scientific purposes. Due to the retrospective design of the study and in compliance with current regulations, specific informed consent for the study was waived.

Quantitative coronary angiography

Angiographic images were recorded at 15 or 7.5 frames/s by monoplane X-ray systems (Allura Xper FD20, Philips; Artist Q Zeego, Siemens; Innova IGS520, GE). Angiographic projections with minimal overlap and foreshortening were selected pre- and post-PCI for the donor arteries and post--PCI for the CTO artery. The selected views were analyzed offline by experienced operators in an official and regularly audited corelab (Cardiovascular Imaging Core Laboratory of the Shanghai Jiao Tong University School of Medicine, Shanghai, CN) using computerized edge-detection quantitative coronary angiography software (QAngio XA 7.3,

Medis Medical Imaging System BV, Leiden, the Netherlands).

Angiographic assessment of coronary collaterals

The overall collateral supply to the CTO--artery was evaluated by the Rentrop classification [12]. Rentrop grade 0 was excluded because such CTO cases are not amenable for PCI.

The primary collateral donor artery (PCDA) was identified as the vessel making the largest collateral contribution, according to collaterals visible on angiography [10]. The other non-CTO major coronary artery was then labelled as the secondary collateral donor artery (SCDA). Collaterals stemming from each donor artery were assessed according to the CC grading [10]. If only CC0 connections were visible, the PCDA was adjudicated according to anatomic criteria (left dominance, hypoplastic left circumflex artery, etc.) or indirect signs of filling; SCDA was then disregarded.

All angiograms were independently analyzed offline by 2 experienced interventional cardiologists (F.D. and W.S.), blinded to computational calculations and independent from the angiographic corelab. In the case of disagreement, the final judgement was reached by consensus with participation of a third interventional cardiologist (J.L.G.C.) acting as referee.

Automatic computation of PCDA flow velocity

The coronary flow velocity was automatically computed by means of an improved deep-learning U-Net algorithm [16], recently validated in a previous study [13], with good segmentation performance (mean Dice coefficient values 0.780 ± ± 0.007, 0.722 ± 0.005, and 0.758 ± 0.003 for left anterior descending arteries, left circumflex arteries, and right coronary arteries, respectively) [13]. The length of the vessel was calculated for each frame according to the length of the segmentation centerline [17, 18]. Taking into account the frame rate, the curve of vessel length variation over time (length/time curve) could easily be derived during the phase of contrast injection. The slope of the length/time curve defined the flow velocity in that coronary artery [13, 19, 20]. A paradigmatic example of the flow velocity calculation using the artificial intelligence (AI) software is provided in Figure 1. The comprehensive explanation of the computational process has been appended to the **Supplementary material**.

Calculation of physiology parameters of collateral circulation

The change in collateral flow from the donor to the recipient artery after CTO revascularization is directly proportional to the difference in flow velocity pre-post in the donor artery (Fig. 2): $(V_{DONORpre} - V_{DONORpost})$.

Assuming steady laminar flow conditions and constant vessel diameters, the absolute change in collateral flow ($\Delta\phi_{coll}$) can be estimated as follows: $\Delta\phi_{coll} = (V_{DONORpre} - V_{DONORpost}) \times Area_{DONOR}$, where the flow area is derived from the vessel diameter at the most proximal segment of each donor artery: $Area_{DONOR} = \pi(diameter/2)^2$.

The change in collateral flow index (ΔCFI) is defined as the $\Delta\phi_{coll}$, expressed as the proportion of the antegrade flow in the CTO vessel after restoration of its patency: $\Delta CFI = \Delta\phi_{coll} / \Delta\phi_{CTO}$.

$\Delta\phi_{CTO}$ can be calculated, following the same rationale as above, as the product of the flow velocity post-PCI and the flow area at the most proximal segment of the CTO artery: $\Delta\phi_{CTO} = V_{CTOpost} \times Area_{CTO}$.

This way, ΔCFI would be finally calculated as: $\Delta CFI = [(V_{DONORpre} - V_{DONORpost}) \times Area_{DONOR}]/[V_{CTOpost} \times Area_{CTO}]$

ΔCFI is an approximation to the CFI defined by previous studies on collaterals physiology, using Doppler or a pressure wire [10, 21–23] or fractional collateral flow [24], and it can be defined as the flow supplied by the collaterals, expressed as a proportion of the normal flow in the CTO artery after revascularization. Because collateral flow does not fully collapse after CTO revascularization, but gradually decreases over time [21, 22, 25, 26], ΔCFI is only an approximation to CFI, losing accuracy proportionally to the persistence of collateral circulation after PCI.

Statistical analysis

Continuous variables were expressed as mean ± standard deviation, and categorical variables were described as counts and percentage. Analysis of normality was performed with the Kolmogorov--Smirnov test. Continuous variables were compared using ANOVA, Kruskal-Wallis H, or Mann-Whitney U test, as appropriate, while categorical variables were compared with Pearson's χ^2 test or Fisher's exact test, as appropriate. Paired serial flow velocities of the PCDA and SCDA before and immediately after successful CTO recanalization were compared with the paired t-test or Wilcoxon test, stratified according to Rentrop classification or CC grading. All statistical analyses were performed using SPSS

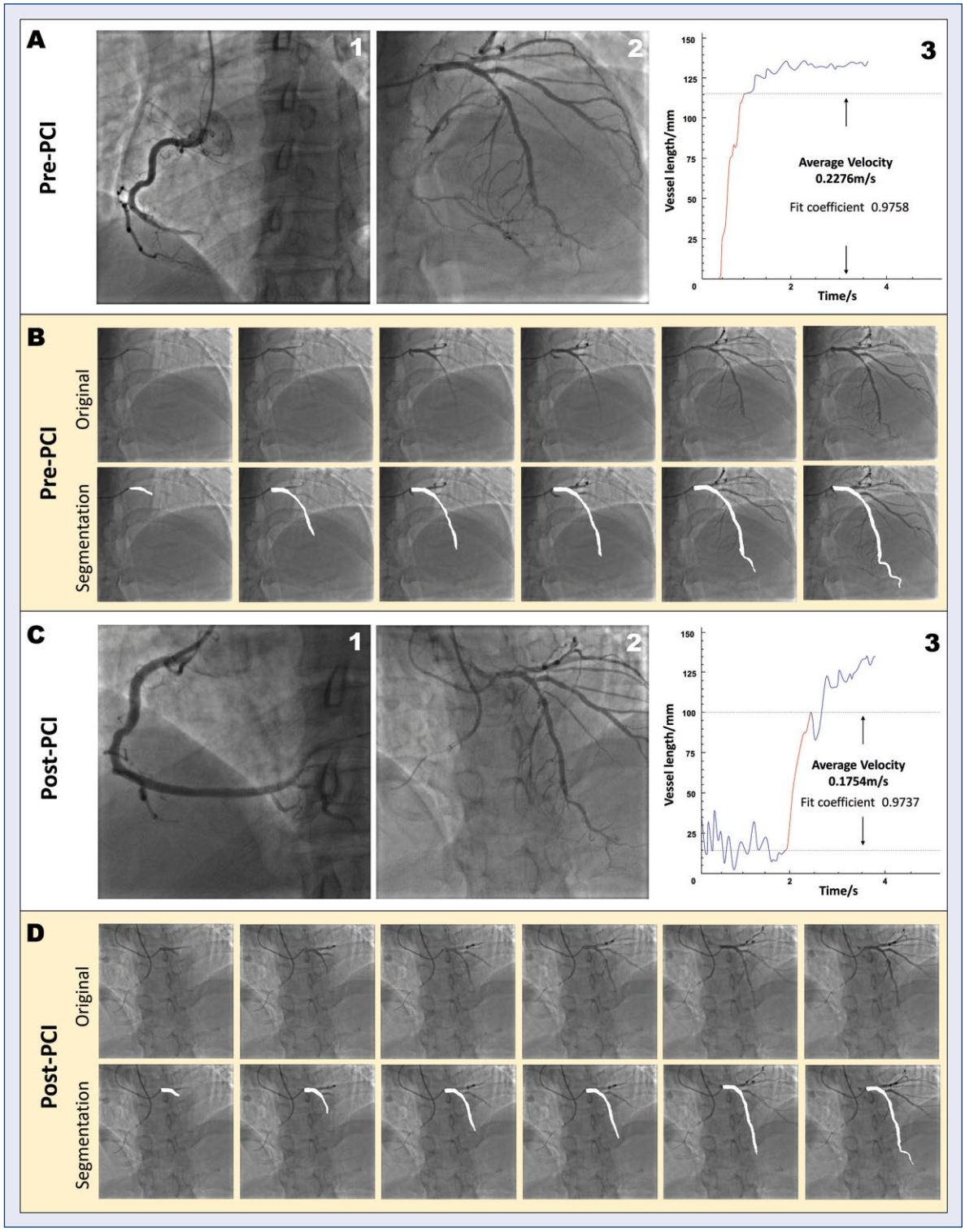

Figure 1. Paradigmatic example of automatic flow velocity calculation using the artificial intelligence (AI)-aided software. Chronic total occlusion (CTO) of the distal right coronary artery (RCA), proximal to the crux cordis (**A1**). The left anterior descending artery (LAD) was the primary collateral donor artery (**A2**). The AI software automatically segmented the LAD and analyzed the contrast filling at baseline angiography (**B**) and rendered the length/time curve (**A3**). The slope during the phase of contrast injection (in red) allowed calculation of the average flow velocity (**A3**). After successful CTO intervention (**C**), the AI software automatically segmented the LAD in the final angiography (**D**) and calculated the flow velocity following the same methodology (**C3**). Notice how the flow velocity decreased in the donor artery. This change in velocity permits changes to be inferred in flow attributable to the closure of collaterals; PCI — percutaneous coronary intervention.

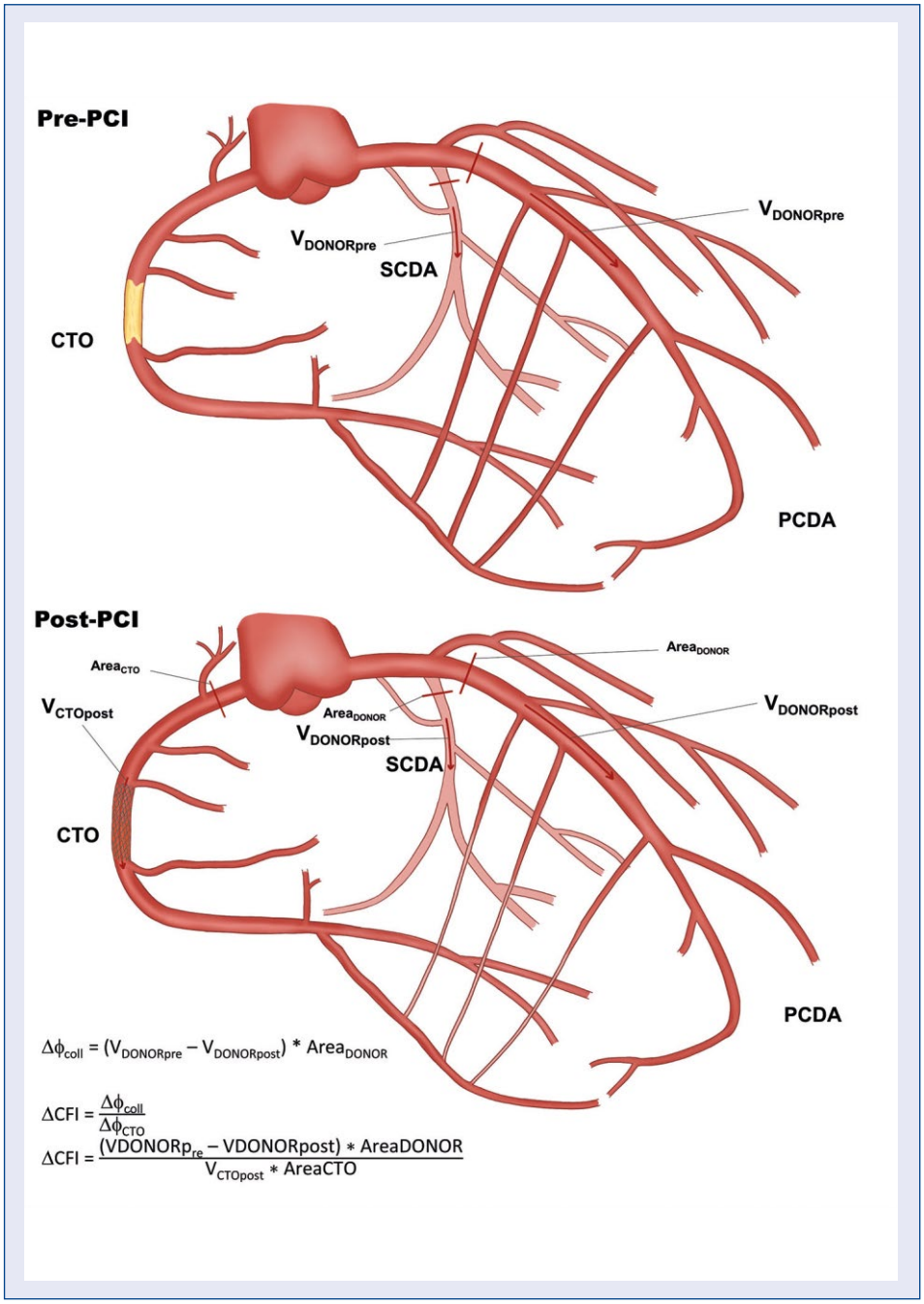

Figure 2. Scheme for the calculations of collaterals physiology. The change in collateral flow ($\Delta\phi_{coll}$) is proportional to the difference in velocity pre-post measured in each donor artery ($V_{DONORpre} - V_{DONORpost}$). From this principle, the different parameters of collaterals physiology are calculated, some of them expressed as the proportion of the antegrade flow in the chronic total occlusion (CTO) artery after restoration of its patency; CFI — collateral flow index; PCDA — primary collateral donor artery; SCDA — secondary collateral donor artery; PCI — percutaneous coronary intervention; $V_{DONORpost}$ — flow velocity in the donor artery post-PCI; $V_{DONORpre}$ — flow velocity in the donor artery pre-PCI; V_{CTO} — flow velocity in the CTO artery post-PCI.

version 22.0.0 (IBM Corporation, Armonk, New York, USA) and R version 3.6.3 (R Foundation for Statistical Computing, Vienna, Austria). A 2-sided p value < 0.05 was considered as statistically significant.

Results

Baseline characteristics

A total of 130 patients with single-vessel CTO and an indication for revascularization underwent

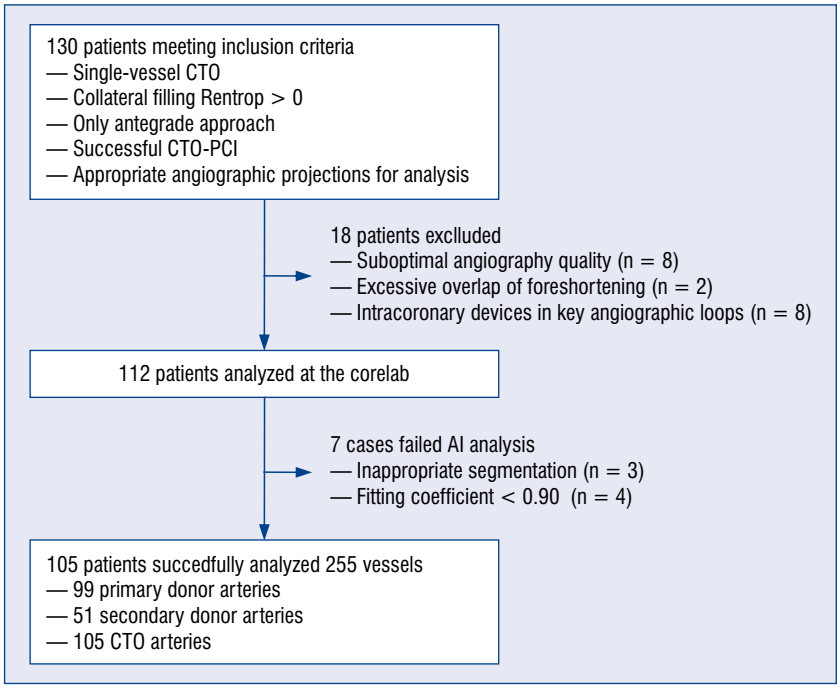

Figure 3. Flow-chart of the study; CTO — chronic total occlusion; PCI — percutaneous coronary intervention; AI — artificial intelligence.

successful PCI between December 2016 and January 2021 in the participating centers. Eighteen cases were excluded due to insufficient angiography quality (8 cases), excessive overlap or foreshortening (2 cases), or the presence of intracoronary devices in the angiographic loops required for the analysis (8 cases), thus resulting in 112 patients analyzed at the corelab. In the analysis phase, the AI software failed to correctly segment the donor artery in 3 cases, and the fitting coefficient of the length/time curve was < 0.90 in 4 cases, resulting in 105 patients suitable for analysis (Fig. 3). The number of vessels analyzed was 255, including 99 PCDA, 51 SCDA, and 105 CTO-arteries. Forty-two (16%) vessels in 35 (33%) patients required minor manual assistance for the frame selection prior to automatic flow computation, whilst in the rest of the cases the AI analysis was completely run in a fully-automated fashion for both frame selection and flow computation.

Patients were grouped by Rentrop classification [12] and CC grading [10]. Rentrop collateral filling was graded as 1, 2, and 3 in 10 (10%), 37 (37%), and 52 (53%) patients, respectively. There were no significant differences in baseline clinical and lesion characteristics between patients in the different Rentrop groups, except for hyperlipidemia, which occurred more frequently in patients with Rentrop grade 1 (**Suppl. Table 1**). CC grading in the PCDA was CC0, CC1, and CC2 in 4 (4%), 37 (37%), and 58 (59%) patients, respectively, while in the SCDA 21 patients had CC0 (41%), 30 patients had CC1 (59%), and no patient had CC2 collateral channels. The baseline clinical and lesion characteristics did not differ between groups, except for hypertension, which occurred more frequently in patients with CC grade 0 in the PCDA (**Suppl. Table 1**).

Flow changes in the donor arteries after CTO revascularization

Flow velocities in the donor arteries pre-procedure did not significantly differ among patients, irrespective of the Rentrop or CC classification of their collateral circulation (Table 1). However, significant differences in flow velocity and derived parameters were observed in the PCDA among Rentrop groups after CTO revascularization. The pre-post change in flow velocity was ranked in parallel to the initial Rentrop filling: 0.02 ± 0.01 m/s for Rentrop 1, 0.04 ± 0.01 m/s for Rentrop 2, and 0.07 ± 0.02 m/s for Rentrop 3, with significant differences in the contrasts between categories (Table 1). Consequently, the pre-post change in collateral flow ($\Delta\phi_{coll}$) and the ΔCFI were directly

Table 1. Automatic assessment of collaterals physiology in donor arteries before and after chronic total occlusion (CTO) revascularization, stratified according to the Rentrop and collateral connections (CC) classifications.

Collateral circulation classifications	Rentrop 1	Rentrop 2	Rentrop 3	P	CC0	CC1	CC2	P
Pre-procedure								
Velocity of PCDA [m/s]	0.25 ± 0.07	0.22 ± 0.05	0.25 ± 0.06	0.13	0.22 ± 0.03	0.25 ± 0.06	0.23 ± 0.06	0.22
Velocity of SCDA [m/s]	0.25 ± 0.03	0.20 ± 0.05	0.21 ± 0.05	0.09	0.20 ± 0.06	0.21 ± 0.04	–	0.49
Post-procedure								
PCDA:								
Velocity [m/s]	0.23 ± 0.06*	0.18 ± 0.05	0.19 ± 0.05	0.05	0.21 ± 0.02	0.21 ± 0.06§	0.17 ± 0.05	0.01
Change in flow velocity [m/s]	0.02 ± 0.01*‡	0.04 ± 0.01‡	0.07 ± 0.02	< 0.001	0.01 ± 0.01†	0.04 ± 0.02†	0.06 ± 0.02	< 0.001
Change in collateral flow ($\Delta\phi_{coll}$) [mL/s]	0.20 ± 0.17‡	0.34 ± 0.17‡	0.55 ± 0.27	< 0.001	0.13 ± 0.10†	0.35 ± 0.20§	0.51 ± 0.27	< 0.001
ΔCFI	0.13 ± 0.15†	0.24 ± 0.17	0.35 ± 0.25	0.01	0.05 ± 0.04†	0.22 ± 0.14§	0.35 ± 0.25	< 0.001
SCDA:								
Velocity [m/s]	0.23 ± 0.01	0.18 ± 0.05	0.18 ± 0.05	0.07	0.19 ± 0.06	0.18 ± 0.04	–	0.58
Change in flow velocity [m/s]	0.02 ± 0.01	0.02 ± 0.02	0.02 ± 0.01	0.46	0.01 ± 0.01	0.03 ± 0.01	–	< 0.001
Change in collateral flow ($\Delta\phi_{coll}$) [mL/s]	0.19 ± 0.14	0.13 ± 0.12	0.16 ± 0.11	0.54	0.06 ± 0.08	0.21 ± 0.09	–	< 0.001
ΔCFI	0.15 ± 0.14	0.08 ± 0.09	0.09 ± 0.06	0.50	0.04 ± 0.06	0.13 ± 0.07	–	< 0.001

In Rentrop classification group, significant differences compared with Rentrop 2: *p < 0.05; compared with Rentrop 3: †p < 0.01, ‡p < 0.001. In CC classification group, significant differences compared with CC2: §P < 0.05, †P < 0.01; PCDA — primary collateral donor artery; SCDA — secondary collateral donor artery; CFI — collateral flow index

proportional to the initial Rentrop classification (Table 1). Conversely, no significant differences between Rentrop groups could be found for the SCDA in flow velocity or any other derived parameter of collaterals physiology.

Likewise, the pre-post change in flow velocity was proportional to the CC grading in the PCDA: 0.01 ± 0.01 m/s for CC1, 0.04 ± 0.02 m/s for CC2, and 0.06 ± 0.02 m/s for CC3 (Table 1). Thereafter, $\Delta\phi_{coll}$ and ΔCFI were also directly proportional to the CC classification. The CC classification was more sensitive than Rentrop in detecting changes in collateral flow for the SCDA; SCDA with CC1 collateral circulation had larger changes in flow velocity after CTO revascularization than SCDA with CC0 collaterals (0.03 ± 0.01 vs. 0.01 ± 0.01 m/s, $p < 0.001$), and subsequently in $\Delta\phi_{coll}$ (0.21 ± 0.09 vs. 0.06 ± 0.08 mL/s, $p < 0.001$) and ΔCFI (0.13 ± ± 0.07 vs. 0.04 ± 0.06, $p < 0.001$). There was no case of SCDA with CC2 collateral circulation (Table 1).

Paired individual flow velocity changes in the donor arteries after CTO revascularization

Flow velocity in the PCDA was significantly higher at baseline than after CTO revascularization. This observation applied to 98 (99%) patients, irrespective of the Rentrop (Fig. 4) or CC classification (Fig. 5). Nonetheless, when the PCDA had CC0 collaterals, the change in velocity was less intense, even negligible in some cases, so the change did not reach statistical significance in this subgroup (n = 4).

As for the SCDA, the flow velocity also changed after CTO revascularization. This change was also observed in 46 (90%) patients and reached statistical significance in Rentrop 2 and 3 groups, but not in Rentrop 1 (n = 3) (Fig. 4). The change was also significant irrespective of whether the collaterals in the SCDA were CC0 or CC1 (Fig. 5). Interestingly, the change in flow velocity for CC0 collaterals was quantitatively similar to the one observed in the PCDA, but the difference was significant for the analysis of the SCDA (n = 21) while non-significant for the analysis of the PCDA (n = 4) (Fig. 5).

Paired individual differences between PCDA and SCDA in flow velocity change after CTO revascularization

For each patient, the change in flow velocity after CTO revascularization was larger at the PCDA than at the SCDA (0.05 ± 0.02 m/s vs. 0.02 ± 0.01 m/s, $p < 0.001$) (**Suppl. Fig. 1**).

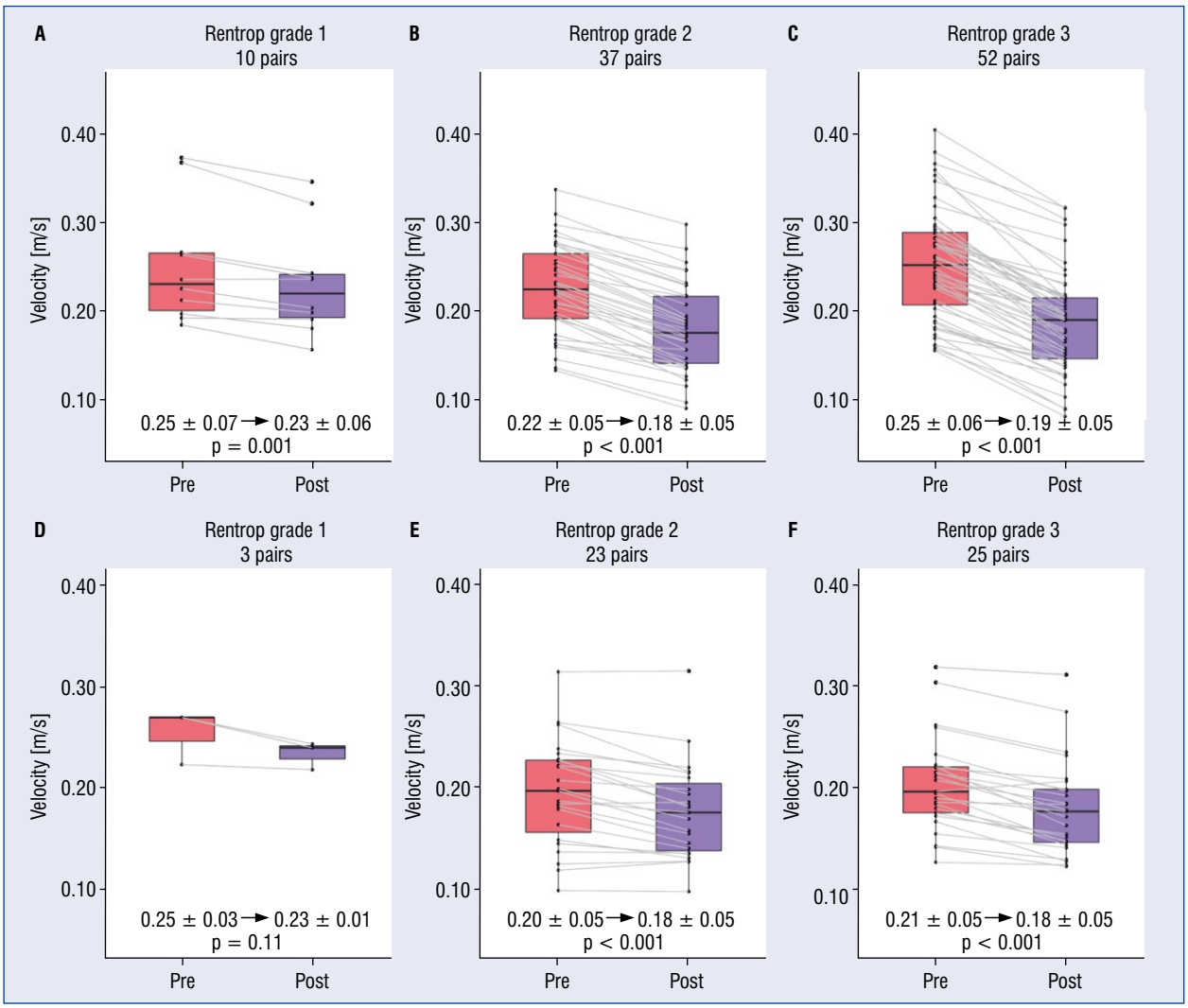

Figure 4. Flow velocity changes in donor arteries after successful chronic total occlusion percutaneous coronary intervention (CTO PCI), stratified according to Rentrop classification in the CTO artery: primary collateral donor artery (upper panels) and secondary collateral donor artery (lower panels). Primary collateral donor artery in CTO patients with Rentrop 1 (**A**), Rentrop 2 (**B**), and Rentrop 3 (**C**); secondary collateral donor artery in CTO patients with Rentrop 1 (**D**), Rentrop 2 (**E**), and Rentrop 3 (**F**).

Discussion

To the best of our knowledge, this is the first study to propose a novel computational method to evaluate the physiology of collaterals in CTO, based on the analysis of the angiographic filling of donor arteries, using a deep convolutional model of AI. The consistency of the results with current knowledge about collaterals physiology strongly suggests the validity of the method to estimate collateral circulation in CTO [10, 21, 25, 27]. Our study proves a change in flow velocity and subsequently in parameters estimating the collateral flow after successful revascularization [21, 27] in a proportional quantity to the angiographic grading of collaterals, according to both Rentrop or CC classifications [10, 27], with a larger reduction in the PCDA than in the SCDA consistently observed in each case.

The main advantage of this approach is the use of conventional angiography for the analysis, without the requirement of additional devices or dedicated filming. The only condition is acquiring the angiography free of intracoronary devices (e.g., wires or microcatheters) at the beginning and at the end of the intervention, which is usually fulfilled as part of the standard procedure in most expert CTO centers. The use of AI enables a fully auto-

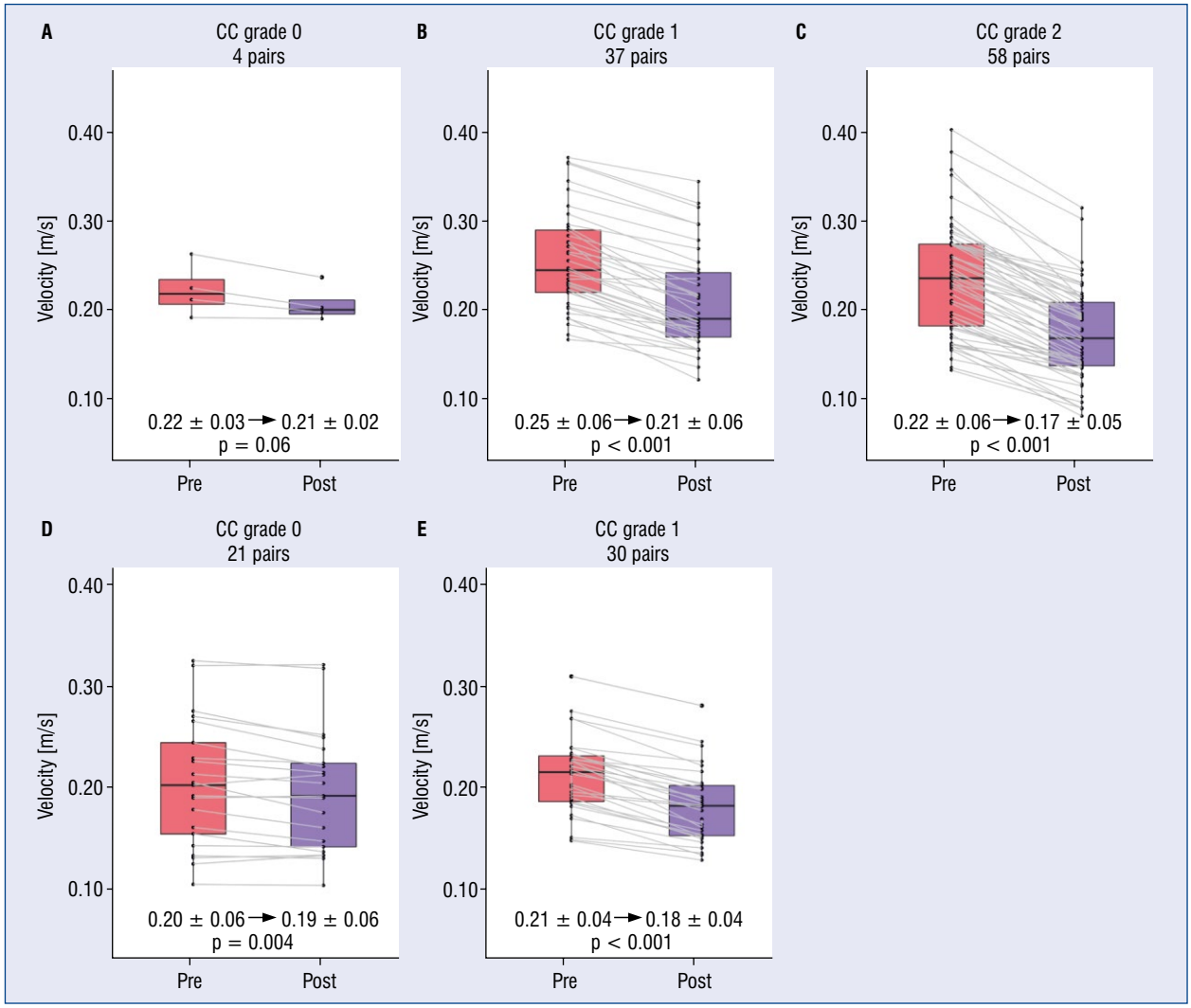

Figure 5. Flow velocity changes in donor arteries after successful chronic total occlusion percutaneous coronary intervention (CTO PCI), stratified according to the collateral connections (CC) grading from the donor artery: primary collateral donor artery (upper panels) and secondary collateral donor artery (lower panels). Primary collateral donor artery with CC0 collaterals to the CTO artery (**A**), CC1 (**B**), and CC2 (**C**); secondary collateral donor artery with CC0 collaterals to the CTO artery (**D**) and CC1 (**E**). No secondary collateral donor artery presented CC2 connections in the current study.

matic process that can be completed with minimal human interaction in a timely manner for routine clinical implementation. In our study 105 out of 112 patients could be analyzed; this means a feasibility of 93.75%, which is much higher than conventional invasive methods for this aim. These characteristics permit massive assessment of collaterals physiology in large databases, both prospectively and retrospectively.

The current method focuses on the donor arteries rather than the CTO artery, similarly to previous studies on collaterals physiology and coronary steal [28, 29]. The possibility of evaluating the collateral circulation in multiple donor arteries is an asset of computational physiology that opens interesting research opportunities on unexplored nuances. Other invasive methods, especially using Doppler wire, could theoretically explore the collateral circulation in multiple donor arteries, but such a study would become prohibitively complex. Conversely, computational physiology can easily provide all this functional information without altering the standard workflow of the CTO intervention. A good example of unexplored features of collaterals circulation is the reduction in collateral flow from the SCDA after CTO revascularization,

even though the collateral channels were classified as CC0. From an interventional point of view, this finding is very interesting, and it points out that in most cases the perfusion of the CTO territory depends on multiple donor vessels, even though its contribution is not always apparent in angiography.

A final advantage of AI is its objectivity and reproducibility, as compared with the intrinsic subjectivity of angiographic classifications like Rentrop or CC grading. In this regard, the persistence of collateral circulation at the end of the procedure might objectively point to suboptimal perfusion flow or to the loss of a substantial number of small branches, perfusing a critical mass of subtended myocardium. This might be interesting, to objectively refine the current definition of technical success in CTO-PCI. Other potential clinical implications of this novel method might point to an eventual prognostic value of the collateral closure, which could be evaluated in sequential follow-up studies. The hypothetical prognostic value might be determined not only by the technical success, but also by the viability of the subtended myocardium, both theoretically playing a role in the changes in collaterals physiology. Likewise, the method might be useful to study phenomena linked to coronary steal [28, 29].

Limitations of the study

This was a retrospective study, thereby with the intrinsic limitations of this design, and potentially subject to selection bias. This limitation was, however, minimized by the strict application of predefined inclusion/exclusion criteria.

The frame rate is a potential limitation of the current method. Calculating the flow velocity using the slope of the length/time curve should also work at low frame rates; however, most of the studies in our sample were acquired at 15 frames/s. Only 1 case was acquired at 7.5 frames/s that could be successfully analyzed. Nevertheless, the accuracy of the method at 7.5 frames/s is essentially unknown and should be specifically addressed in future studies. This might be relevant, because many experienced centers use low frame rates as default for CTO procedures. Nevertheless, it is currently recommended that the angiographic loop be recorded for collateral assessment at 15 frames/s, irrespective of the frame rate chosen for the rest of the intervention.

The retrograde approach was excluded from this initial study to minimize the effect of persistent collateral circulation due to manipulation of the collateral channels during the retrograde access. A proper assessment of the current method in cases of retrograde approach is warranted. Likewise, microvascular dysfunction associated with CTO [30] might introduce some variability in the parameters assessed in this study.

This pilot study tested the consistency of computational findings with previous knowledge about collaterals physiology. The lack of a head-to-head comparison with intracoronary Doppler or pressure wire is a substantial limitation, and a comparison of this method with invasive absolute coronary blood flow determined by thermodilution is also essential, which should be addressed in future studies.

Conclusions

Automatic assessment of collaterals physiology in CTO is feasible, based on a deep-learning model analyzing the filling of the donor vessels in angiography. The changes in collateral flow after successful CTO revascularization obtained with this novel method are quantitatively proportional to the angiographic grading of the collaterals of the PCDA. A significant reduction in collateral flow from the SCDA is also observed after CTO-PCI, even in CC0 collateral connections.

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