

Review article

New Techniques of Recording and Interpretation of Dynamic Coronary Angiography

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ABSTRACT

In the study of coronary artery disease (CAD), the mechanism of plaque formation and development was still the subject of continuing debate. The limitation of the current coronary angiogram (CAG) is that it can only show the static image of a narrowing on the arterial channel without identifying the mechanism of the disease or predicting its progression or regression. Therefore, the current recording of CAGs is reprogrammed by the present team of investigators. The new technique focuses on the identification of blood flow patterns and analysis of their normal or abnormal dynamics by adapting the same methodologies used by hydraulics engineers when moving fluid or gas through domestic or industrial pipes or pumps. This new technique of recording and interpretation of coronary angiography helps to identify different flow patterns in arteries and the application of the fluid dynamics principles to the coronary system. This new technique ushers in a new era of crucial insights and applications regarding the diagnosis, medical, surgical, and interventional management of atherosclerotic diseases.

KEYWORDS Coronary Collision, Dynamic Coronary Angiography, Laminar flow, Turbulent flow, Water hammer shock, Antegrade coronary flow, Retrograde coronary flow.

INTRODUCTION

In the care of patients with coronary artery disease (CAD), one common and important question for clinicians or interventionalists is why many lesions stay unchanged for a long time while a few become severe, unstable or acutely occluded

[1]. Similarly, there is no answer to the question of which factors start a lesion or promote its progression or regression.

In an effort to elucidate the above questions, for the past 5 years, our team changed the strategy and used hydraulics as the main methodology in the investigation of flow in the

coronary, iliac, and femoral arteries. For engineers, laminar flow is considered the ideal fluid in pipes because it maximizes efficiency and preserves equipment life, while turbulent flow damages the inner surface of pipes and components of pumps. Based on the above observations, our research protocols focus on the correlation between turbulent or laminar flow with the presence, progression or regression of atherosclerotic plaques [2], [3]. Practically, the greatest challenge is to record the phenomena, including vortex, water hammer shock or turbulence, etc., elegantly at the location of initial, ongoing growth or plaque rupture in coronary or iliac, or femoral arteries.

In the review of images from an angiogram, besides the time-consuming and labor intense visual screening and identification by junior researchers, the disruptive challenge is to train Artificial intelligence or Machine Learning algorithms to recognize hydraulic phenomena, including vortex formation and degeneration, the collision between the antegrade against the retrograde flow, turbulent flow, etc. [4]-[8].

In this paper, we detail the angiographic techniques of how to capture accurately the images of arterial phenomena (laminar flow, vortices, water hammer shock, collision, etc.) when performing coronary, iliac, and femoral angiograms.

METHODS

New Technique of Dynamic Coronary Angiography. At this present time, the coronary angiography (CAG) technique requires the operators to fill the coronary lumen with contrast. The goal is to detect an indentation of the contrast shadow of the lumen (i.e., “luminogram”), and then label this defect as a lesion or stenosis (Figure 1).

The limitation of current CAG is that it can only show the static image of a narrowing on the arterial channel without identifying the mechanism of disease or predicting its progression or regression. Therefore, the current recording and reviewing technique of CAGs is reprogrammed by the present team of investigators. This new technique focuses on the identification of blood flow patterns and analysis of their normal or abnormal dynamics by adapting the same methodologies used by hydraulics engineers when moving fluid or gas through residential or industrial pipes or pumps [9].

Injection of Contrast and Recording of Images. In the beginning, the contrast medium is injected until the index coronary artery is completely opacified. When some contrast in “black” color is seen ejected back from the coronary ostium into the aorta, the manual injection stops. As the blood enters the vessel, the shape, movements, directions, and interactions of the blood flow in “white” color could be clearly observed and easily identified above a “black” background of contrast [10]. The CAG is recorded from the beginning of injection until all the contrast disappears from the distal arterial vasculature (i.e., arterial phase) (Figure 2 A-D) as the blood finishes displacing the contrast and ends after the contrast is totally flushed out of the coronary veins (i.e., venous phase) (Figure 3 A-C).

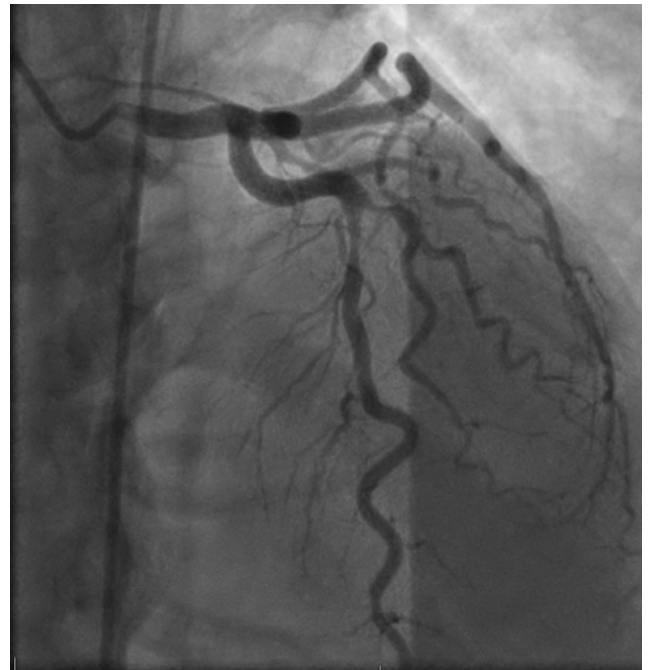


FIGURE 1. The left anterior descending artery (LAD) in the anterior-posterior cranial view. There is a narrowing at the mid-segment of the LAD, distal to the origin of a moderate size diagonal. The current technique of angiography only shows the degree of stenosis without critical information on how the lesion was formed and how it will progress in the near or far future.

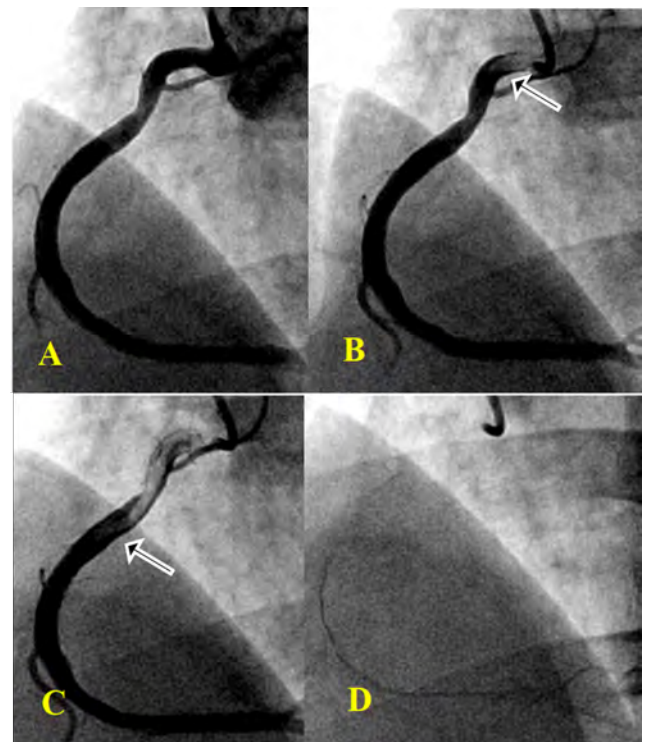


FIGURE 2. Arterial Phase. (A) The artery is full of contrast in black. (B) The blood in white color begins to move in. (C) The blood in white color moves at the mid-segment. The tip of the blood flow is pointed and typical for laminar flow (arrow). (D) The contrast in black is almost washed out of the artery. This is the end of the arterial phase.

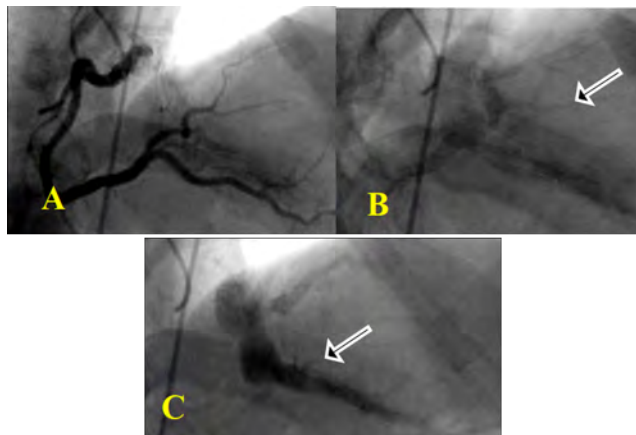


FIGURE 3. The Coronary Venous Flow. (A) The contrast fills all the coronary arteries. (B) Contrast is flushed out of the distal vasculature and goes into the myocardium. (arrow). (C) The contrast fills up the coronary vein (arrow).

During the recording, the camera is positioned at an angle that could record the index artery and vein at their full length, with all the images completely visible within the screen, at 15 images per second (sec) or 0.067 sec or 67 milliseconds (msec) per image (67 msec are the interval between recorded images) or 30 frames per second (or 0.033sec or 33msecs between images). The CAG is saved and stored in the EPIC Electronic Health Record (EHR) System (Epic Systems Corporation, Verona, WI). The recording of 15 fps produces sharper detailed images of the arterial phenomena than the images filmed at 30 fps.

ANGIOGRAPHIC TECHNIQUES

The appropriate views need to be selected so all movements of the blood (and contrast) can be identified accurately on a clean background of the lungs. The selected angles circumvent superimposing the arteriograms or venograms on the bony structures of the spine or on the myocardium filled with contrast at the end of the arterial phase and during the venous phase. The arterial segments and questions on pathological mechanisms when reviewing angiogram are listed in table 1.

The Left Main artery. The left main artery (LM) needs to be delineated at its full length so the entry flow from the aortic root, the hydraulic phenomena at the mid-segment, and the distal bifurcation can be captured. The best views for the ostial LM and mid-segment are (1) the antero-posterior (AP) caudal views (Figure 4 A-B) and (2) the left anterior oblique (LAO) caudal (spider view) (Figure 5 A-D). The flows in the left main could clarify the mechanism of starting a LM lesion, the location of recurrent injuries to promote its growth (upper or lower border), and its change from a stable to a vulnerable plaque. There is a need to search for the best views. In this patient, the LAO caudal views showed well the flow while the RAO cranial view did not (Figure 6 A-B).

The Left Anterior Descending Artery. In the Left Anterior Descending Artery (LAD), the flow to be seen are at the ostium, the outer curve, or the upper border of the proximal

TABLE 1. Questions When Reviewing Coronary, Iliac and Femoral Flows.

- 1 **The left main (LM)** needs to be delineated on its entire length from the ostium to the bifurcation in order to capture all the hydraulic mechanisms of **entry flow** affecting the formation of lesions, their growths, and plaque ruptures at the ostium, mid and distal LM.
- 2 **The transition** from the LM to the left anterior descending (LAD) and left circumflex (LCX) arteries have to be clearly delineated so that all the mechanisms affecting **bifurcated flows** and lesions (laminar or turbulent, primary or secondary, at the center or at the side (boundary layer) at the entry and exit shoulder of the LAD and LCX can be clearly identified, timed and recorded.
- 3 **The proximal segments of the LAD and LCX** need to be seen clearly, especially the outer curve of the proximal LCX. Here usually there is a **boundary layer with its recirculating flow** where mild plaques are most commonly formed.
- 4 **The bifurcations of the LAD with the diagonal and the LCX with the obtuse marginal** need to be delineated for the same reasons as in #2.
- 5 **The mid segment** of the right coronary artery (RCA) and the LAD or LCX where the majority of significant lesions are located. Here is the location of **collision between antegrade and retrograde flow** inflicting the initial injury to the intima and triggering the atherosclerotic process.
- 6 **The distal segment of the RCA** at the junction between the RCA and posterior descending artery (PDA) and posterior lateral branch (PLB) where the majority of distal and slow growth lesions are located.
- 7 **The junction** between the proximal and mid-segment of the RCA where lesion could develop due to **recurrent hinge movement** of the angle connecting the 2 arterial segments.
- 8 The mid-segment of the **iliac artery, the common femoral artery (CFA), the superficial femoral artery (SFA), and the Profunda femoris artery (PFA)**. The mechanism of injury at the CFA, SFA and PDA is most likely due to **deceleration injury** from the retrograde flow secondary to diastolic hypertension.
- 9 **The aortic root** and its flows from the left ventricle and to the coronary arteries (timing of systolic and diastolic flow).

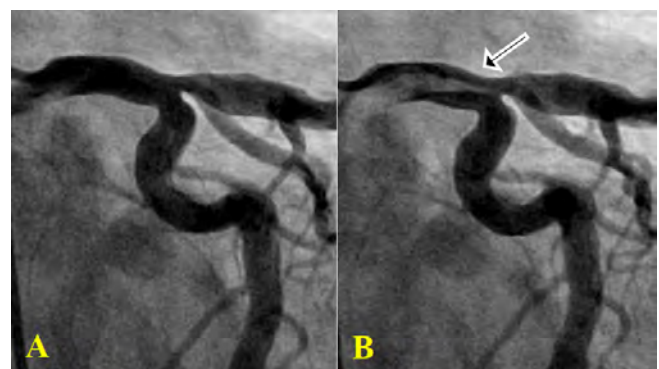


FIGURE 4. The antero-posterior (AP) caudal views. (A) The left main coronary artery (LM) is seen well with the bifurcation of the left anterior descending artery (LAD) and left circumflex (LCX). There is a narrowing at the ostium of the LAD. (B) The blood in white color is seen moving in a laminar pattern with a pointed tip. (arrow) The boundary layers on both sides of the laminar flow are well delineated.

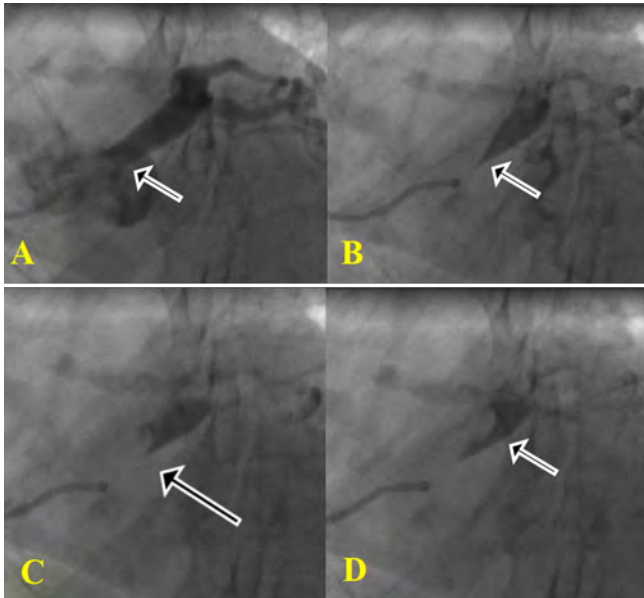


FIGURE 5. The Left Anterior Oblique (LAO) caudal views. (A) The left main coronary artery (LM) is seen well at its proximal and mid segments. The tip of the catheter is outside the LM. (B) Because there is a significant lesion at the distal end of the LM, the contrast forms a thick boundary layer that starts at the mid-segment of the LM and becomes thicker at the distal end of the LM. (arrow). (C) At the beginning of diastole, the blood in white color moves in and first hits the boundary layer at its base (arrow). (D) Then the blood begins to move up toward the center of the flow. (arrow) The importance of pictures C and D is that the blood hits the lower border of the LM first. In case of a lesion, the jet of blood would hit the base of a plaque, could rupture its cover, and start acute coronary syndrome, including total collusion of ST segment elevation myocardial infarction.

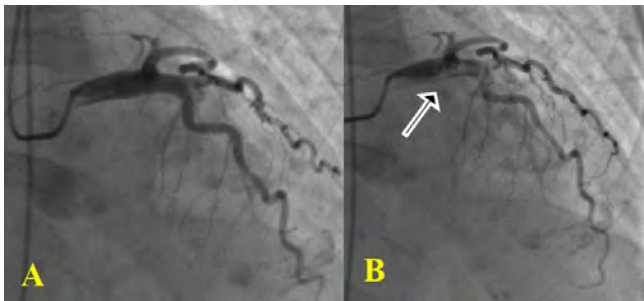


FIGURE 6. The Right Anterior Oblique (RAO) cranial views. A-B These are the 2 pictures of the left main (LM) of the patient in figure 5. The RAO cranial view does not show well the flow in the LM.

segment where there is low shear stress and preferential formation of plaques and at the midsegment where there is the majority of lesions secondary to a collision between the antegrade and retrograde flow [11]. The best views for the ostial and mid-segment LAD are:

- 1) The left anterior oblique (LAO) caudal (spider view) for the ostium (Figure 7 A-B).
- 2) The antero-posterior (AP) cranial views for the proximal segment (Figure 8 A-D).
- 3) The LAO Cranial view for the mid and distal segments (Figure 8 A-D).

The Left Circumflex Artery. In the left circumflex artery (LCX), the flow to be seen is at the ostium, the outer curve

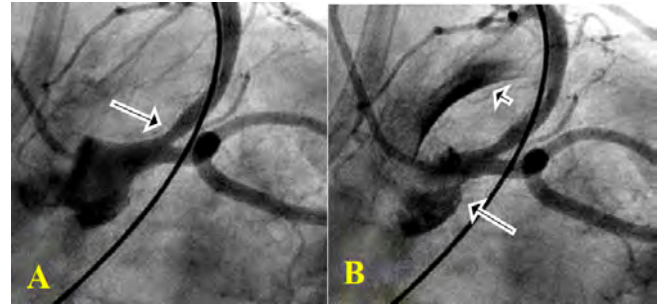


FIGURE 7. The Left Anterior Oblique (LAO) caudal (Spider view). These are the 2 consecutive images of the left main (LM) in the spider view. They are separated by 0.06 seconds (recorded at 15 frames per second). (A) In this view, the ostium of the left anterior descending (LAD) artery is seen well. The flow going through would be seen well (arrow). (B) In this view, the contrast in black color could be seen ejecting from the aortic root and coronary sinus into the ascending aorta. (arrowhead) These features help to time the flow in the coronary artery.

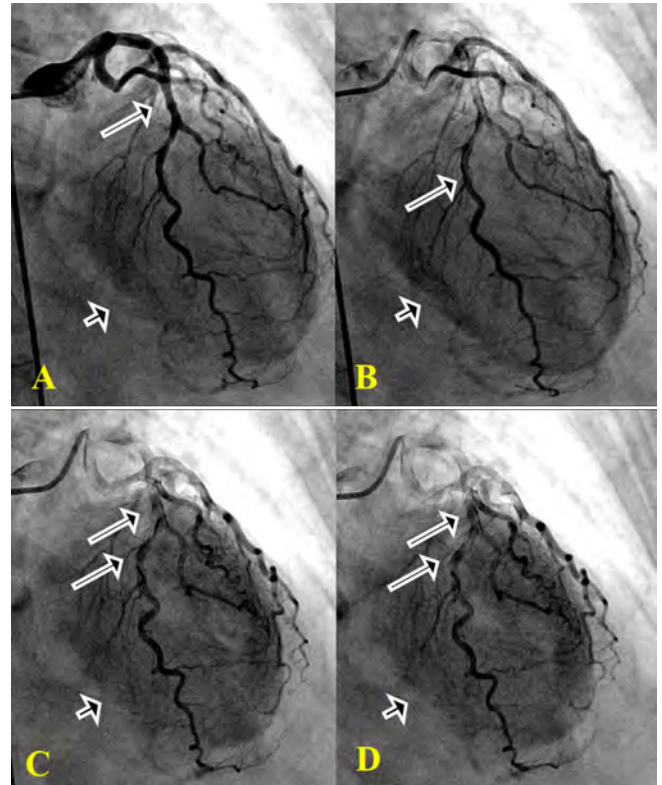


FIGURE 8. The antero-posterior cranial views. The antero-posterior (AP) cranial views are best for the flow in the proximal segment. Pictures A and B are consecutive angiographic images 0.06 seconds apart from each other. (A) The left anterior descending artery (LAD) is full of contrast in black. (B) In diastole, as the left ventricle looks larger (arrowhead), the blood in white moves in and reaches the mid-segment, distal to the origin of a large diagonal (arrow). C-D At the beginning of systole, the left ventricle looks smaller (arrowhead). Black contrast is seen moving back (in a retrograde direction) to the midsegment of the LAD, proximal to the origin of a large diagonal. The images of these abnormal flows are important in the flow study and are speculated to be the cause of lesions in the proximal segment of the LAD while sparing the mid-LAD (Figure 9).

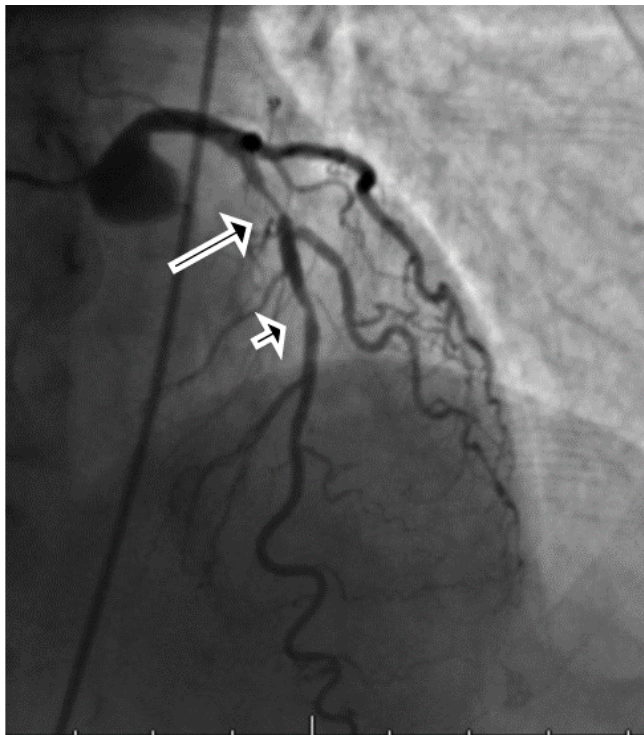


FIGURE 9. The lesions in the proximal segment of the left anterior descending artery. In this patient, there is a severe subtotal lesion in the proximal segment of the left anterior descending artery (LAD) (arrow). There is no lesion or only a mild lesion (arrowhead) in the mid-segment of the LAD, distal to the origin of a large diagonal. Why is there a lesion here? Is there a mechanical flow that damages the intima and starts the atherosclerotic process?



FIGURE 10. The Anterior Posterior (AP) caudal views. These are the pictures of the left main (LM) and the left circumflex artery (LCX). **A** Both arteries are filled with contrast. **B** The blood in white moves in, however, the blood fills the left anterior descending artery first then 0.06 seconds later, will turn the corner and move into the LCX (arrow).

opposite to the carina, the mid-segment, or the branches of the obtuse marginal (OM). The best views for the ostial and mid-segment LCX are (1) the AP caudal view or the right anterior oblique (RAO) caudal which shows well the ostium and proximal segment of the LCX and the branches of the OM. The AP caudal view is used when the proximal segment of the LCX is not tortuous. The right anterior oblique (RAO) caudal is better when the proximal segment is curved or tortuous (Figure 10 A-B).

The Right Coronary Artery. In the right coronary artery (RCA), the flow to be seen are listed in table 2.

The best view for the flow at the ostial, proximal, and mid-

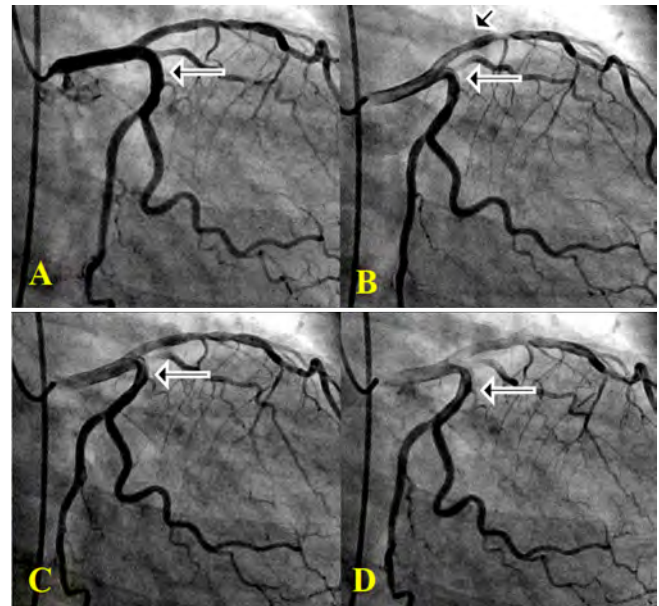


FIGURE 11. The Anterior Posterior (AP) caudal views. These are the pictures of the left main (LM) and the left circumflex artery (LCX). **A** Both arteries are filled with contrast. **B** The blood in white moves in, however, the blood fills the LAD first then 0.06 seconds later, turns the corner and moves into the LCX. The blood in white color hits the inner curve at the carina side first (arrow). **C-D** In these pictures, the blood in white color (arrows) needs to rotate and twist. If the speed of the flow is high enough, a vortex could be formed, and turbulent flow may follow. These abnormal flows may damage the intima and start the atherosclerotic process [12].

TABLE 2. List of Locations to be Focused in the Right Coronary Artery.

- | | |
|---|------------------------------------------------------------------------------------------------------------------------------|
| 1 | The ostium, its orientation, and the angle formed by the proximal segment of the right coronary artery with the aortic wall. |
| 2 | The angle connecting the proximal to midsegment. |
| 3 | The mid-segment. |
| 4 | The junction between the mid and distal segments. |
| 5 | The distal segment. |
| 6 | The bifurcation with the posterior descending artery and posterior lateral branch. |

RCA is the LAO caudal view (spider view) (Figure 12 A-B). The best view for the flow of the distal RCA with its bifurcation to the PDA and PLB is the LAO cranial view (Figure 12 C).

The Iliac and Femoral Artery. The best view to see the flow from the proximal iliac to the common femoral artery is the LAO caudal view. In this angle, the blood is seen emerging from the pelvis and rising up to the inguinal area. Because the blood follows a smooth curve, laminar flow could be formed. However, to see the flow of the iliac artery to the common femoral artery (CFA) and its bifurcation to SFA and PFA, and then the RAO or AP view would delineate the bifurcation better (Figure 13 A-B). The first important phenomenon to be captured and deciphered is the collision of the antegrade against the retrograde flow in the iliac artery (Figure 13 B). The second important arterial phenomenon is the formation of a vortex at the level of the iliac artery

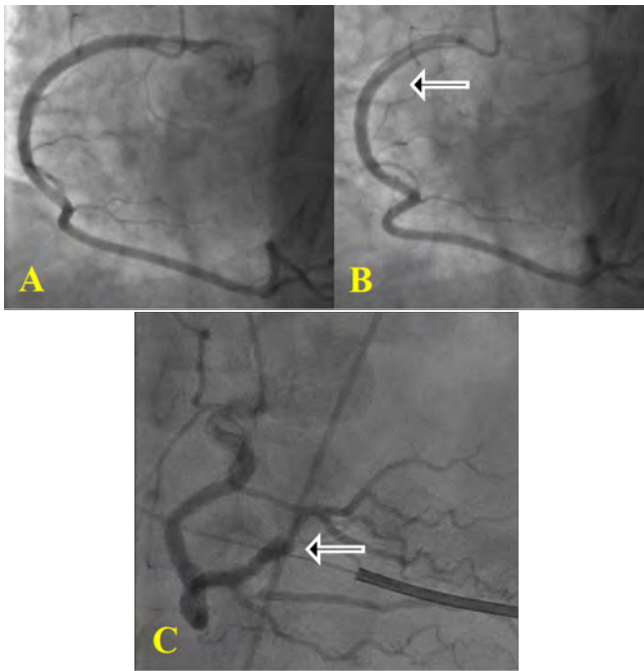


FIGURE 12. The Anterior-Posterior (AP) caudal views (A-B) and The Anterior-Posterior (AP) cranial views (C). **A** The right coronary artery is filled with contrast. **B** The blood in white moves in a laminar fashion with a pointed tip (arrow). **C** Here, the focus is on the distal artery with normal antegrade flow. However, retrograde flow at the posterior descending artery or distal right coronary artery could be seen during systole due to uncontrolled hypertension.

(Figure 14 A). These vortices degenerate into turbulent flow (Figure 14 B). However, the vortices and turbulent flows are short-lived because they are all wiped out at the beginning of systole due to the cyclic pattern of coronary or peripheral flow. The third important arterial phenomenon is the reversed flow due to uncontrolled diastolic hypertension through the mechanism of elevated peripheral vascular resistance (Figure 15).

Software Applications. The software to retrieve and view the angiographic images was the Digital Imaging and Communications in Medicine (DICOM) viewer integrated into the Picture Archiving and Communication System (PACS) system in EPICs or the Viewer from Philips (Koninklijke Philips N.V, Amsterdam, Netherlands) or the stand-alone Viewers RadiAnt (Medixant, Poznan, Poland), Osirix (Pixmeo SARL, Bernex, Geneva, Switzerland) or Syngo Via (Siemens, Erlangen, FR Germany). The authors built their own storage and viewer system using open source software www.https://ohif.org/.

Analysis of Lesion and Flow by ARTIFICIAL INTELLIGENCE Programs. Extensive utilization of Artificial Intelligence and Deep Learning packages and programs were initiated in our research protocols and aimed to optimize the research methodology on arterial lesions and flows, systemize the protocol for angiographic interpretation, and give the preliminary online results without the need for off-line manual image review [4]-[8].

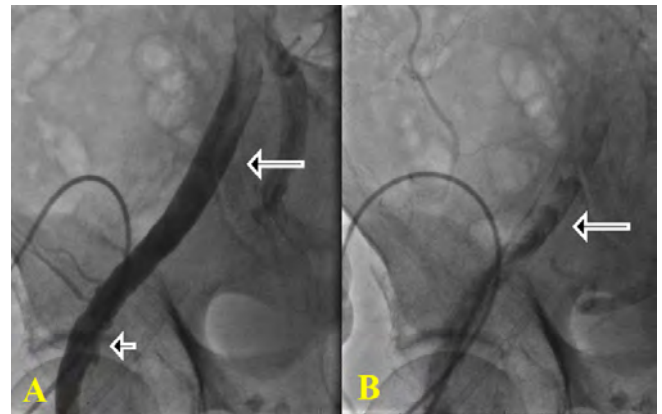


FIGURE 13. The Anterior-Posterior (AP) caudal views. **A** Here, the focus is on the proximal segment of the iliac artery. Because this segment is a smooth curve, during systole, we can see the laminar flow (arrow). **B** During diastole, because of the elevated peripheral vascular resistance, reversed flow is strong. The contrast is seen flowing back and hitting the antegrade flow (arrow) The collision between the antegrade and retrograde flow could generate turbulence, damage the intima, and form atherosclerotic plaques. What could not be explained is that the lesions are seen frequently in the common femoral artery (arrowhead in figure 13 A), while the collision is in the iliac artery (arrow in figure 13 B). This is a question to be solved.

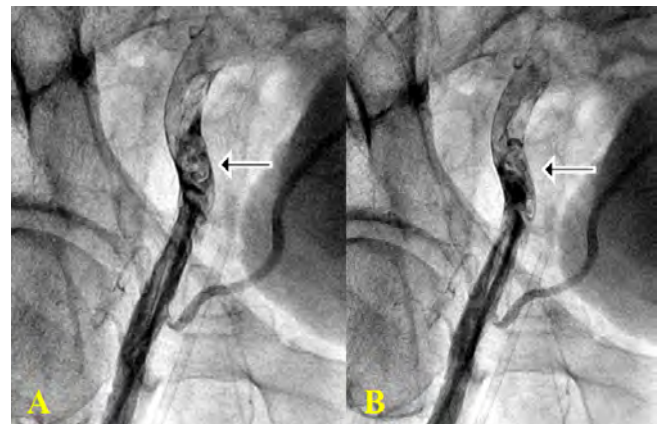


FIGURE 14. Vortex Formation and Degeneration. These two pictures are consecutive images separated by 0.06 seconds (recorded at 15 frames per second). **A** Here, the focus in the proximal segment of the iliac artery is the formation of a vortex. **B** The vortex degenerates into turbulence (arrow). What is the pathological implication of this phenomenon?

CONCLUSION

In the study of CAD, the mechanism of plaque formation and development was still the subject of continuing debate. The new technique of recording and interpretation of coronary angiography helps to identify different flow patterns in arteries. The application of the fluid dynamics principles to the coronary system suggests that the formation mechanism of coronary lesions is most likely due to turbulence resulting from repetitive collisions. This turbulent flow inflicts injuries to the intima, triggering the birth of a small lesion and promoting its growth. When the lesion grows too fast, there is not enough time for its soft cap to harden or become calcified. In the event of uncontrolled hypertension, which exaggerates the repetitive pounding of turbulent flow, the plaque ruptures. This is most likely the pathological mechanism precipitating

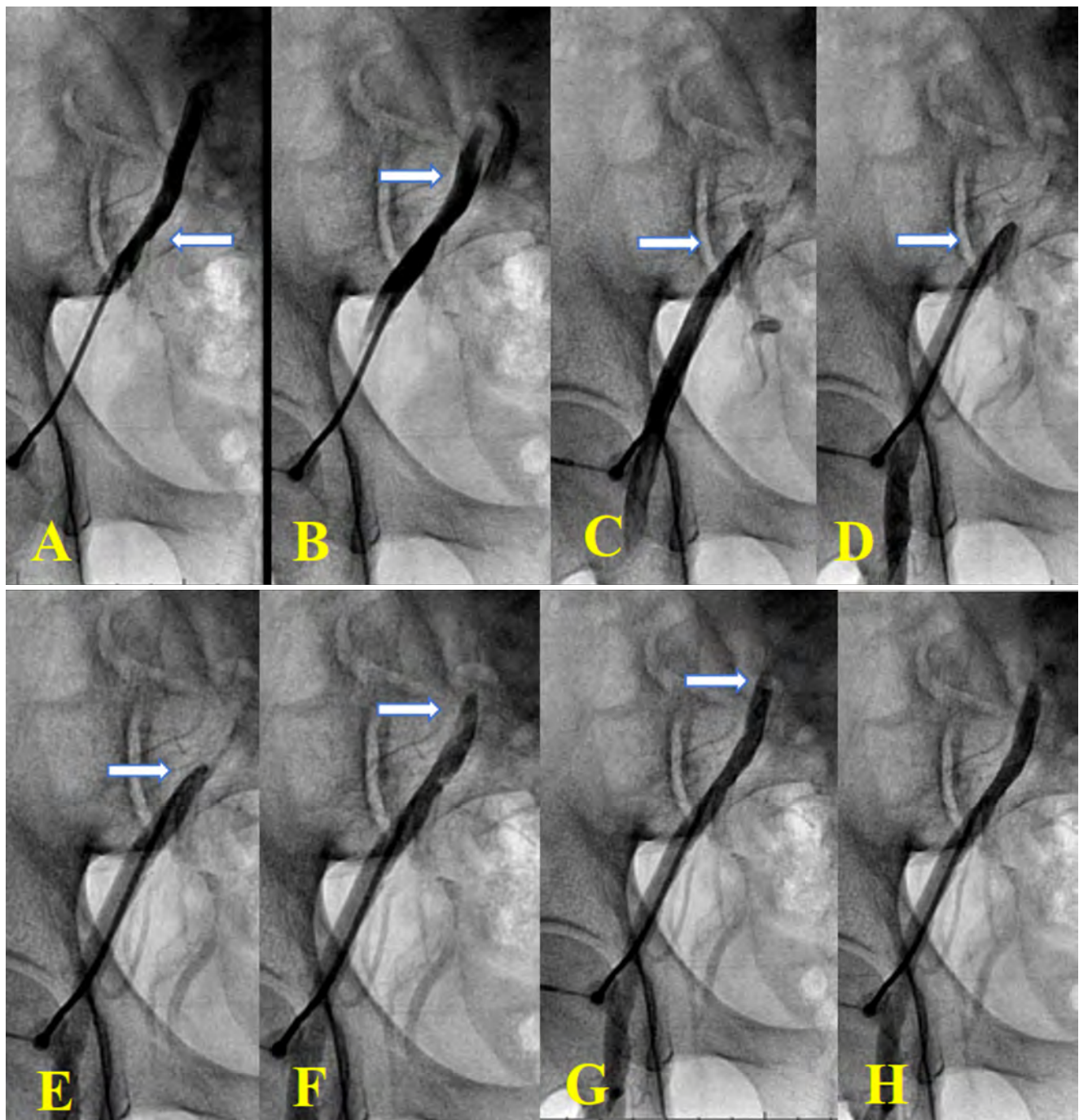


FIGURE 15. Reversed Flow in the Iliac Artery. These are the 8 sequential images separated by 0.06 seconds each (recorded at 15 images per second). **A** At first, the arteries are filled with black contrast. There is a mild lesion at the mid-segment of the right external iliac artery (arrow). **B** In systole, the blood in white flows in an antegrade direction from the heart to the iliac artery. **C** When the blood arrives at the midsegment of the iliac artery, the flow stops (arrow). **D** Now the blood begins to move upwards, in a retrograde direction (arrow). **E-H** Here, the contrast in black continues to move upwards in a retrograde direction. (arrow). What are the pathophysiological implications of this phenomenon? [13].

acute coronary syndrome, ST-elevation myocardial infarction, critical limb ischemia, transient ischemic attack, stroke, etc. This new method of recording and reviewing coronary dynamic flows and their clinical corollaries ushered in a new era of crucial insights and applications regarding the diagnosis, medical, surgical, and interventional management

of atherosclerotic diseases.

CONFLICTS OF INTEREST

None of the authors have conflicts of interest to declare.

REFERENCES

- [1] Gibson C, Karha J, Murphy SA *et al.* "Association of a pulsatile blood flow pattern on coronary arteriography and short-term clinical outcomes in acute myocardial infarction," *Journal of the American College of Cardiology*, 2004, 43:1170–1176, DOI: <https://doi.org/10.1016/j.jacc.2003.11.035>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0735109704001032>
- [2] Truyen TTTT, Ho DT, Vu LT *et al.* "CRT-500.15 Functional Restoration of Laminar Flow Prevented Late In-Stent Restenosis Better Than Anatomical Coronary Cosmetic Reconstruction: An Angiographic, Artificial Intelligence, and Machine Learning Analysis," *JACC: Cardiovascular Interventions*, 2022, 15:S48–S49, DOI: 10.1016/j.jcin.2022.01.202. [Online]. Available: <https://www.jacc.org/doi/abs/10.1016/j.jcin.2022.01.202>
- [3] Nguyen TN, Phan NT, Truyen TTTT *et al.* "Superiority of new dynamic coronary angiography technique by showing antegrade or retrograde, turbulent or laminar flow and simultaneous proximal and distal coronary flows," *Journal of the American College of Cardiology*, 2022, 79:1228, DOI: [https://doi.org/10.1016/S0735-1097\(22\)02219-7](https://doi.org/10.1016/S0735-1097(22)02219-7). [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0735109722022197>
- [4] Vu L, Nguyen T, Nguyen H *et al.* "Training the Machine Learning Programs to Measure the Arterial Phase and Identify the Types of Coronary Flow," *TTU Journal of Biomedical Sciences*, 2022, 1:25–28, DOI: 10.53901/tjbs.2022.10.art04.
- [5] Rigatelli G, Zuin M, Galasso P *et al.* "Mechanisms of Myocardial Ischemia Inducing Sudden Cardiac Death in Athletes with Anomalous Coronary Origin from the Opposite Sinus: Insights from a computational fluid dynamic study," *Cardiovascular Revascularization Medicine*, 2019, 20:1112–1116, DOI: <https://doi.org/10.1016/j.carrev.2019.01.031>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1553838919301034>
- [6] Vu TL, Pham TD, Truyen TT *et al.* "TCTAP A-074 Quantifying Coronary Arterial Stenosis and Measuring the Arterial Phase by Artificial Intelligence Program," *Journal of the American College of Cardiology*, 2022, 79:S46–S48, DOI: 10.1016/j.jacc.2022.03.102. [Online]. Available: <https://www.jacc.org/doi/abs/10.1016/j.jacc.2022.03.102>
- [7] Rigatelli G, Zuin M, Ngo TT *et al.* "Intracoronary Cavitation as a Cause of Plaque Rupture and Thrombosis Propagation in Patients with Acute Myocardial Infarction: A Computational Study," *Journal of translational internal medicine*, Jun. 2019, 7:69–75, DOI: 10.2478/jtim-2019-0014, PMID: 31380239.
- [8] Rigatelli G, Zuin M, Bilato C *et al.* "Coronary artery cavitation as a trigger for atherosclerotic plaque progression: a simplified numerical and computational fluid dynamic demonstration." *Reviews in cardiovascular medicine*, Feb. 2022, 23:58, DOI: 10.31083/j.rcm2302058, PMID: 35229549.
- [9] Nguyen T, Chung D, Ngo L *et al.* "Challenges of the 21ST Century: Part 2 - Dynamic angiography in the investigation of cavitation in coronary arteries: Standard description of coronary lesions and blood flow," *European Journal of Anatomy*, 2021, 25:9–28. [Online]. Available: <https://dash.harvard.edu/handle/1/37370506>
- [10] Nguyen TN, Talarico Jr. EF, Phúc LXM *et al.* *Dynamic Coronary Angiography and Flow*, ch. 2. John Wiley Sons, Ltd, 2020. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119383031.ch2>
- [11] Talarico EJ, Nguyen T, Pham NH *et al.* "Challenges of the 21st Century: Part 3 - The anatomical risk factors which predict future disaster," *European Journal of Anatomy*, 2021, 25:29–46. [Online]. Available: <https://dash.harvard.edu/handle/1/37370508>
- [12] Nguyen T, Vu L, Rigatelli G *et al.* "Measuring the boundary layers in patients with acute coronary syndrome by dynamic angiography and machine learning program," *Journal of the American College of Cardiology*, 2021, 77:1377, DOI: 10.1016/S0735-1097(21)02735-2.
- [13] Nguyen TN, Che WH, Ly LT *et al.* "Abstract 9796: Identification of an Optimal Blood Pressure by Images of Correction of the Pathological Mechanism by Hypertension: An Angiographic, Machine Learning Analysis and Application for Personalized Medicine," *Circulation*, 2022, 146:A9796–A9796, DOI: 10.1161/circ.146.suppl_1.9796. [Online]. Available: https://www.ahajournals.org/doi/abs/10.1161/circ.146.suppl_1.9796