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Questions on the Genesis and Growth of Coronary Lesions and their Answers Based on Fluid Mechanics Engineering: A New Dynamic Angiography Analysis

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ABSTRACT

In the continuing debate regarding the mechanism of atherosclerotic plaque formation in arteries, one question remains unanswered: While all arteries in a patient are exposed to the same systemic risk factors (hypertension, diabetes, aging, nicotine of cigarettes, etc.), why do plaques frequently present in the coronary arteries, and to a lesser extent in the arteries of the lower extremities, and still less in the carotid or renal arteries? Over the past five years, in order to find an answer to the above question, there has been a radical shift in our research strategy: The principles of fluid dynamics in industrial and domestic pipes/pipelines were employed to decipher changes in the cardiovascular system. The types of flow under investigation included laminar, entrance, turbulent, and helical flows in systole and diastole, as well as the interface between antegrade and retrograde flows resulting in water hammer shock and cavitation phenomena. We aim to highlight the similarities and differences among flow types in arteries and pipes, and to apply the same methodologies to study the formation, growth, and rupture of coronary plaques leading to inactive and active clinical syndromes as well as the beneficial mechanism of percutaneous coronary interventions (PCI). In this article, we list the questions and the answers based on the main data of several completed studies and the preliminary results of ongoing projects from a fluid mechanics perspective. The angiographic coronary images of recirculation flow, vortex formation, collision, hammer water shock, and cavitation will be showcased in details, and their videos in slow motion are uploaded in the addendum for further in-depth review.

KEYWORDS Cavitation, Water hammer shock, helical flow, turbulent flow, Dynamic Coronary Angiography

INTRODUCTION

Currently, explanations for the genesis and growth of atherosclerotic coronary lesions remain elusive and unconvincing. In the quest for new strategies and methodologies in coronary artery research, the present team of investigators has turned to the field of fluid mechanics, examining the patterns of damage seen in industrial pipes and pumps. By applying the same fluid mechanics theory and practice to the cardiovascular system, our new hypothesis was built on the concept that flow abnormalities damage the intima and prompt the formation, growth, and/or rupture of atherosclerotic plaques [1]-[3]. When a patient received multiple coronary angiograms (CAGs) over the course of years or underwent staged percutaneous coronary interventions (PCI), the approach was to search for the transformation from one type of flow to another and to correlate these flow dynamics with the appearance, severity, growth, regression, or rupture of lesions. To support the detailed investigation of coronary or peripheral flow, the current technique of angiography was redesigned and reprogrammed so it could provide precise details of flow movements, such as changes in direction, intensity, and speed [4], [5].

This article serves as a roadmap for researchers and readers to understand the rationale behind classifying lesions by flow type, and it also aims to decipher the similarities and differences observed when comparing flows and lesions in coronary arteries versus those in pipes. One important ongoing project employs fluid mechanics to explain the beneficial mechanisms of control-fracturing coronary plaques with plain balloon angioplasty (POBA), shaving the calcified superficial layers with rotational atherectomy, weakening the calcified wall with intravascular lithotripsy, or scaffolding the arterial lumen with a bioabsorbable vascular scaffold (BVS) or the struts of a stent. In this article, an overview of questions and answers generated from completed studies and preliminary results of ongoing research will be presented. The angiographic coronary images of recirculation flow, vortex formation, collision, hammer water shock, and cavitation serve will be showcased in details and their videos in slow motion are uploaded on the addendum for further in-depth review.

METHODS

NEW Technique of Filming and Reviewing Coronary Angiography

According to current practice, the CAG technique requires the operators to fill the coronary lumen with contrast to detect a defect or indentation of the contrasting shadow of the lumen (i.e., "luminogram") and subsequently classify such a defect as a lesion or stenosis. This technology can only show the static image of a narrowing of the arterial channel without explaining the mechanism of the disease or predicting its progression or regression. Therefore, to examine the dynamics of the blood flow in more details, the current recording and reviewing techniques of CAGs were redesigned and reprogrammed by the present team of investigators. This new technique focused on the flow itself, identifying its patterns and analyzing its abnormalities based on the same methodology used by fluid mechanic engineers in domestic and industrial pipes [5]. A detailed description of the method was previously published, and a short summary is presented below [5].

First, the contrast was injected until the index coronary artery was completely opacified. When some contrast (colored black) was seen ejected back from the coronary ostium into the aorta, the manual injection was halted. At this moment, the blood (visualized as white) moved in quickly to displace the contrast. The shape, movements, directions, and interactions of the blood flow in white could be clearly observed upon the black contrast background. The CAG was recorded from the beginning of injection until all the contrast disappeared from the distal arterial vasculature (i.e., arterial phase), and ended after the contrast was no longer visible in the coronary veins (i.e., venous phase).

During the recording, the camera was positioned at an angle that could record the index artery and vein in their full length, with all the images completely within the limits of the frame, at 15 images per second (sec), or an interval of 67 milliseconds (msec) between images [3]. The angiograms were saved and stored in the EPIC Electronic Health Record (EHR) System (*Epic Systems Corporation*, Madison, WI).

TABLE 1. Questions to be Asked When Seeing a Coronary Lesion Based on Fluid Mechanics Engineering Perspective

1. What is its severity?
2. Where is its location? At the ostium? At the proximal, middle, or distal segment?
3. How is it related to a nearby bifurcation or side branch? Proximal to the bifurcation? Distal to the bifurcation? At the ostium of the distal main vessel? At the ostium of the side branch?
4. Why does it happen here, instead of at a different location of the coronary system? All segments of the 3 coronary arteries are under the effects of the same risk factors if there are: hypertension, diabetes, smoking, high cholesterol level, aging, etc.). What is the fluid mechanic mechanism?
5. Was the mechanism of formation of the lesion similar to the mechanism causing damage inside a pipe or pump? Could it be a collision, vortex formation, turbulence, water hammer shock, cavitation or recirculation flow?
6. How did the lesion grow? Did it grow fast, or did it grow slow? After 40 or 50 years? Or after a few months?
7. What did the distal flow change as the lesion became more severe? How did the new flow affect the formation and growth of new lesions downstream?
8. What were the effects on coronary flow after the lumen is enlarged and scaffolded by a stent?

QUESTIONS on the Genesis, Growth, Rupture, and Demise of Coronary Lesions

Once there is a lesion of every degree of severity (mild, moderate to severe), there many questions to be asked about its birth, growth, rupture, or demise (becoming a chronic total occlusion) are listed in Table 1. Different types of lesions and questions are included in Figure 1.

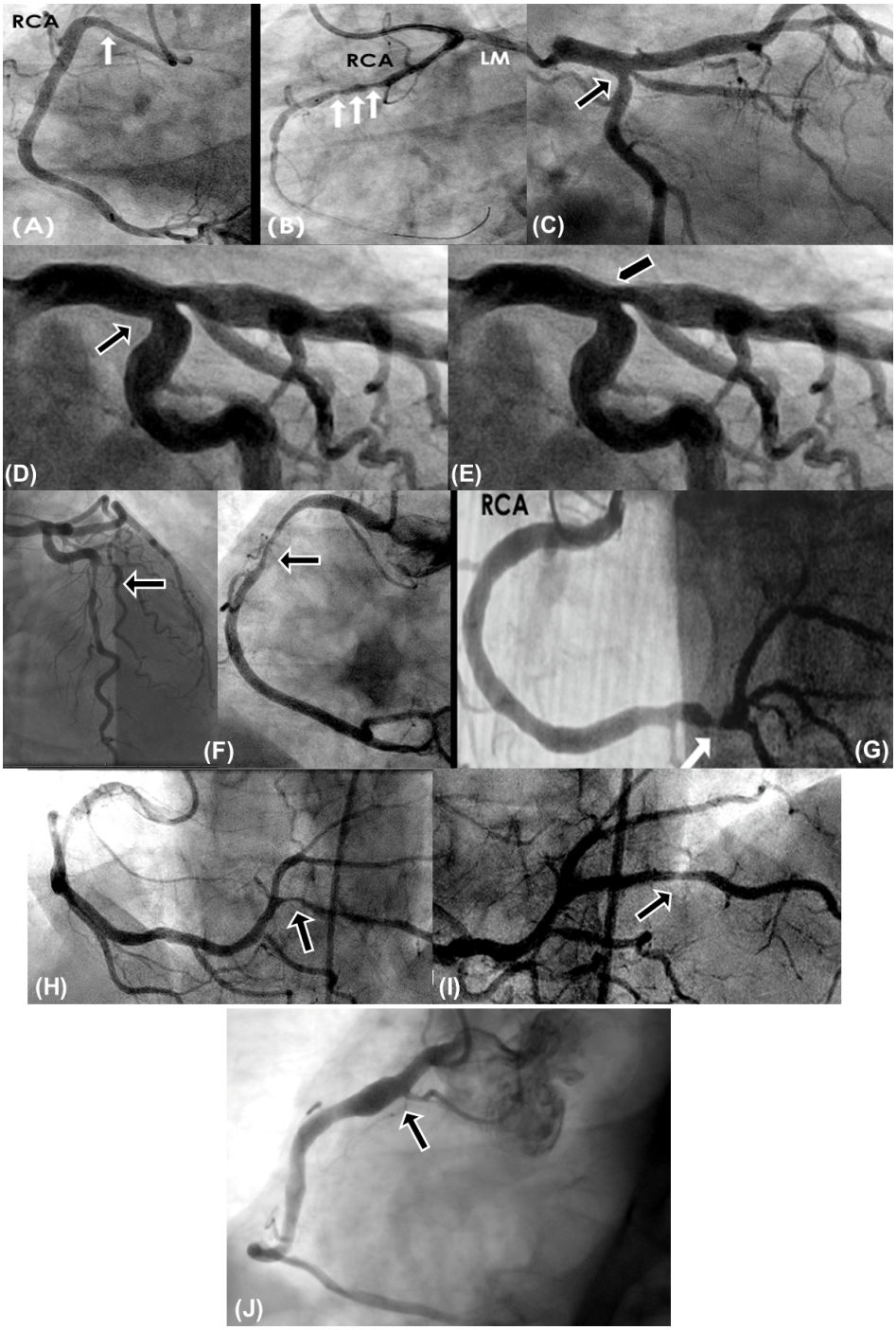

FIGURE 1. **(A-B)** These right coronary arteries had anomalies at the origin of the proximal segment.
(C) The lesion at the ostium of the left circumflex artery is the most common coronary lesion. Is the plaque built up at the outer curve of the proximal segment due to recirculating flow?
(D) What is the cause of the lesion at the ostium of the left anterior descending artery?
(E) What is the cause of the lesion at the end of the left main artery?
(F) Why did the lesion appear at the mid segment of the right coronary artery and the left anterior descending artery? Was it because of turbulence created by the collision of antegrade and retrograde flow at these locations?
(G) Why did a lesion happen proximal to the bifurcation of the right coronary artery and the posterior descending artery? Was it because of the abnormal flow from a retrograde direction?
(H) Why did a lesion happen at the ostium of a posterior descending artery? Was it due to hypoperfusion leading deposit of debris (which could be low density lipoprotein (LDL) molecules) at this slow flow area?
(I) Why did a lesion happen at the mid segment of a posterior descending artery (PDA) after stenting of the ostium of the PDA? Could it be due to the cavitation phenomenon?
(J) Why did the mid segment of the right coronary artery become enlarged or underwent aneurysmal change?

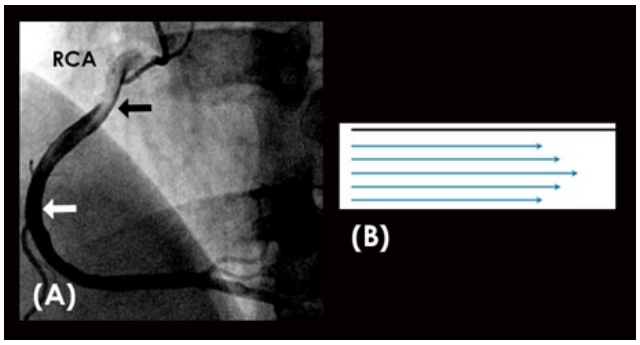

FIGURE 2. Laminar Flow. (A) This is the angiogram of the right coronary artery (RCA), which is completely filled with contrast in black (white arrow). The blood (in white) is seen flowing in order, with a pointed tip where the speed is highest (black arrow). This is called laminar flow. **(B)** Schematic diagram of laminar flow layers (blue) through the arterial lumen (black line represents the arterial wall).

METAMORPHOSIS OF FLOWS

Normal baseline flow in a coronary artery is laminar and is based on the ideal anatomy of the segment. As the artery curves gently, the laminar flow may divide into separation flows with recirculating layers. When these recirculating layers grow larger, they can form vortices. If the vortical flows become substantially large, they are no longer able to control their movement and consequently collide against each other, merge together, lose their organized structures, and become turbulent. When the arterial wall becomes calcified and rigid, the blood flow may form a boundary layer due to high friction upon the wall. At the entry of a bifurcation, if a large part of the flow is preferentially channeled to the main branch, less fluid may be available to smaller side branches. Due to slower flow from undersupply, such arteries may undergo chronic spasms or experience the gradual accumulation of debris along their outer banks. As a result, the remaining channel of flow becomes narrower.

LAMINAR FLOW

Laminar flow is defined as a flow pattern characterized by organized fluid layers with steady velocity and minimal or absent boundary layers. The central layers flow faster with a characteristic pointed tip, while the lateral layers flow at a slower speed due to friction at the wall [6](6)(Figure 2). Laminar flow is the ideal flow of fluid or gas in pipes, tubes, channels, rivers, veins, or arteries. This is due to the fact that there is no damage to the lining of pipes or destruction of the components of the pump with laminar flow. Drawing from the fluid mechanics perspective, if the flow is laminar, there is also no damage to the artery, vein, or vascular structures (mitral, aortic, tricuspid, or aortic valves).

ENTRANCE FLOW

Entrance flow in the hydraulics industry refers to the flow of fluid at an entrance of any cylindrical object such as a pipe, tunnel, etc. When delivering water to a neighborhood or oil to an industrial complex, the flow from the source may be turbulent or laminar. Once inside the pipe, tunnel, pipelines,

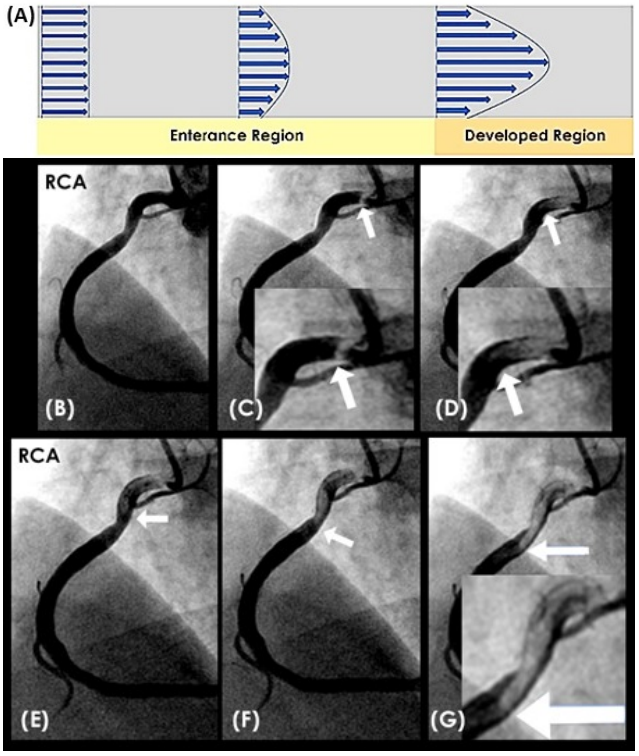

FIGURE 3. (A) A Schema of an entrance flow with change from turbulent to laminar flow. **(B-G)** Images of the Entrance Flow

or pumps, the flow should be converted to laminar, so it does not precipitate damage to the interior wall, transportation equipment, or components of the pump or delivery system. How is this change in flow pattern from turbulent to laminar achieved? In fluid mechanics, the change from one type of flow to another depends on the hydraulic conditions at the downstream segment. The change from turbulent to laminar is depicted in a schematic in Figure 3A.

Dynamic Coronary Flow Perspective

Based on principles of fluid dynamics, all the layers of blood in the angiogram shown in Figures 3B-G enter the right coronary artery (RCA) at the same speed seen with a "flat" leading front (Figure 3C) [7]. As the blood moves forwards, the layers nearest to the vessel's border encounter friction and slow down (Figure 3D). As the flow continues, the central layers move faster, forming the "tip" which is a morphological characteristic of laminar flow (Figure 3E-G). Thus, the term "entrance length" can be used to describe the distance that flow must travel after initially entering the ostium to become fully developed or laminar [7].

HELICAL FLOW

When entering a gentle curve with large diameter, fluid or blood advances in a helical pattern. Helical flow is defined as the normal rotational motion of fluid or blood orientated to the central axis during its passage through an artery [8]. (Fig4) In helical flow, the streamlines in the arterial lumen

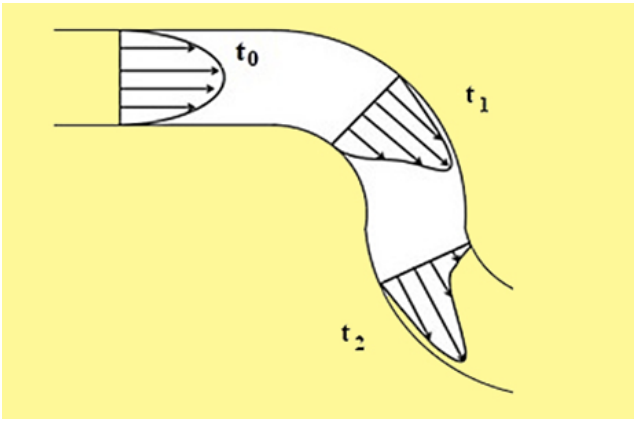

FIGURE 4. **Velocity Map.**

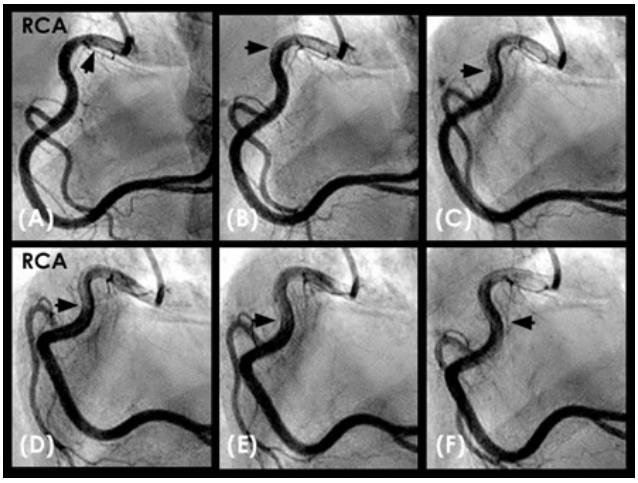

FIGURE 5. **Helical Flow. (A-F)** The blood (in white color) is observed moving along the apices of the curves (black arrowheads). The contrast (in black) with high viscosity occupies the inner curve. The contrast moves from one inner curve (first white arrow) to another inner curve (second white arrow). In these images, the blood in white clearly flow on the right side of the tract, because this location on a straight line connecting the next bend while the contrast flows on the left side (inner curve). **(D-F)** At this stage, the blood in white continues to flow straight (assuming that a straight line is the shortest distance between 2 points), cross the midline in order to reach the left side of the tract. In this position, the blood again is on a best straight line to the next bend.

demonstrate a helical shape, while the cross-sectional view exhibits secondary rotations. The result is a cork-screw type of laminar flow with a leading apex.

Review of a RCA angiogram reveals that upon entrance from the ostium, blood (in white color) is seen twisting, turning along the curves, and reaching the apex in each of four curves. At the same time, the contrast (in black color) moves more slowly from the inner curve to the center of the flow to reach the next inner curve (black arrow, Figure 55A-F).

Fluid Mechanics Perspective

When flow occurs in a helical pattern, is there any similarity to the paths taken by the racing cars at Formula 1 or the Indy 500? For car racing enthusiasts, the critical moment and location to watch are when curving around a corner (or "cornering" as coined by car racing industries) [9]. (Figure

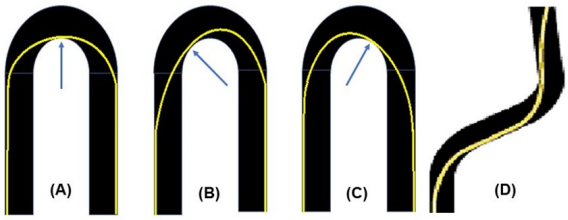

FIGURE 6. **Location of the apex with Turn in point and the path taken by the coronary blood (A-D).**

66A-D) The overarching tactical question is how to navigate corners safely before pushing the throttle up to maximum, blasting in a roaring thunder to the next corner. Ultimately, the strategy remains that the speed at the turning point may be at any level, even slower. However, the speed at the exit must be fast to pursue the shortest path to the next corner [9].

Dynamic Coronary Flow Perspective

In the coronary artery, blood flows by passive influences, there is no conscious decision to accelerate or stop. The most interesting question for cardiologist is whether the natural path taken by the blood flow seen in Figure 77A-F is the most efficient way. For the coronary artery, it would be simpler if there were no need to decrease the speed by changing the direction of coronary flow, as sudden and excessive decelerations or changes in direction require energy, create recirculating flows, and ultimately cause turbulence.

SEPARATION FLOW

Based on studies using fluid mechanics, bifurcation lesions may be divided into two types: (1) those proximal to the bifurcation and (2) those at the ostial or proximal segment of the side branch or main vessel.

Fluid Mechanics Perspective

When fluid flowing in a laminar fashion needs to round a bend (i.e., curve), the principles of fluid dynamics state that every element of the fluid must act uniformly over the whole cross-section of the pipe (or artery) [1]. If the differences in speed and pressure between the layers of the center and two borders is too high, separation of flow can occur (Figure 8).

Dynamic Coronary Flow Perspective

In case of a lesion distal to the bifurcation and at the proximal segment of a large side branch (SB), the distribution of recirculation flow occurs at the outer curve of the SB, with the flow in an antegrade direction (Figure 99A-C). In the case of a lesion proximal to the bifurcation, the recirculation flow occurs at the same side of the major vessel, due to abnormalities created by the flow in a retrograde direction. (Figure 1010A-C). These lesions were slow growing, and their growth could be controlled if the speed of the flow

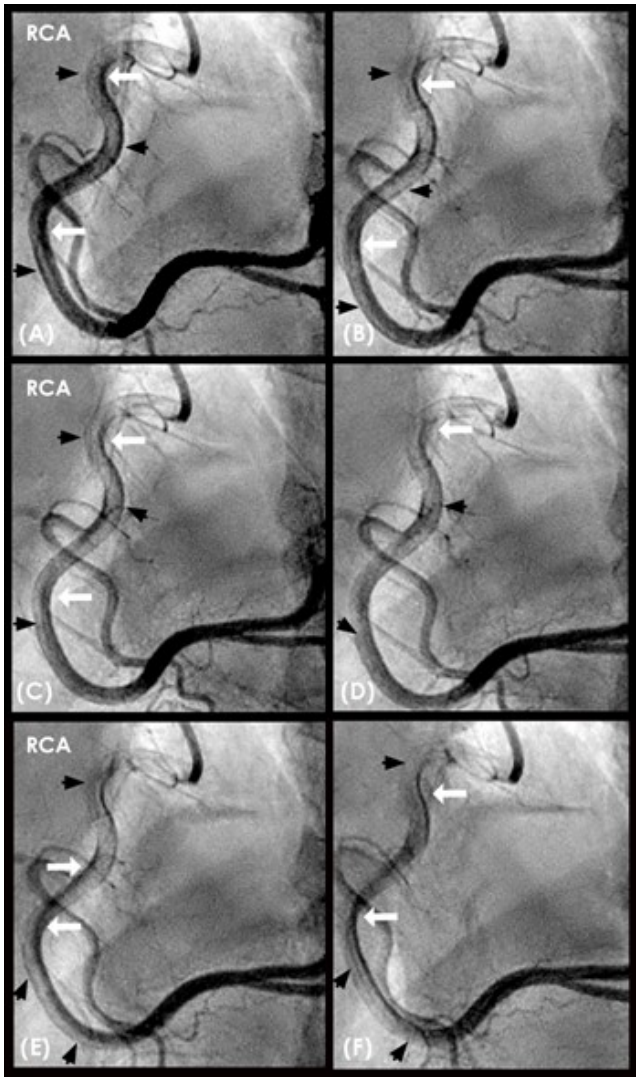

FIGURE 7. **Flow movement in the Right Coronary Angiogram (A-F).**

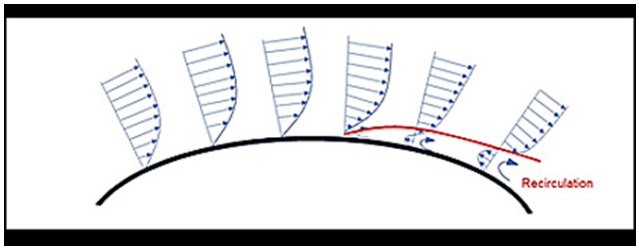

FIGURE 8. **Separation of Flow and Recirculating Layers.** Schema of the flow velocities when entering a curved slope with recirculating layers and subsequent turbulence.

was lower. At a slower speed, the recirculation flow at the confluent area of the main vessel or at the outer curve of the SB was abolished, so there was no further accumulation of debris. With less change of pressure or shear stress, there was less chance for the soft cover of a lesion to be struck repetitively by the blood flow. As a result, the cover was not ruptured, and the lesion could not grow.

VORTEX FORMATION AND TURBULENCE DEGENERATION

In fluid dynamics, turbulent flow is defined as an irregular, disorganized flow made unpredictable by vortices, eddies, and wakes. Turbulence transpires when fluid flows at high speeds in pipes with large diameters, based on the formula used to calculate the Reynolds number [10] (Figure 11). The mark of turbulent flow in an angiogram is a randomly disorganized mixing of blood (white) and contrast (black).

COLLISION in Pipes

How does turbulent flow develop in a mechanical or bio-vascular system? In the setting of a tank or a pipe with one valve at the proximal end and one valve at the distal end, what happens to the flow if the distal valve is suddenly closed? (Figure 12.A-C). In the beginning, as the proximal valve opens, water from the tank travels towards the distal valve. As the distal valve closes, the column of proximal fluid continues to traverse the pipe, with the leading edge of the column striking the closed valve. As a result, the distal column of fluid begins to compress. A pressure wave (i.e., shock wave) is generated and travels back towards the tank or towards the proximal valve. The shock wave travels back and forth between the two ends until it finally dies down due to energy lost from friction (Figure 12A-C) [11].

Vortex and Turbulence Formation in Arteries

As the shock wave from a retrograde direction hit the antegrade flow, how did the blood flow behave at the collision site? At the beginning of a series of 6 consecutive images of an iliac angiogram, at first, the contrast was injected into the iliac artery until it completely filled the lumen. (Figure 13A) One image or 0.067 seconds later, the blood in white was seen flowing in, on an antegrade direction, with a pointed laminar tip curving along the apex (Figure 13B white arrow). However, 0.067 seconds later, the laminar flow was stopped abruptly, with all the layers of the tip collapsing on each other like a falling stack of dominoes (Figure 13C white arrow). 0.067 seconds later, a swirl of mixed blood and contrast appeared on the apical side of the iliac artery, similar to cigarette smoke in the classic experiments of flow dynamics (white arrow). The rudimentary vortex was created, resulted from a collision between the 2 forces coming from the antegrade and retrograde direction. The antegrade flow was powered by the systolic contraction of the left ventricle and the retrograde flow was generated from the excessive constriction of the distal systemic vasculature in the feet. (Figure 13A-F)

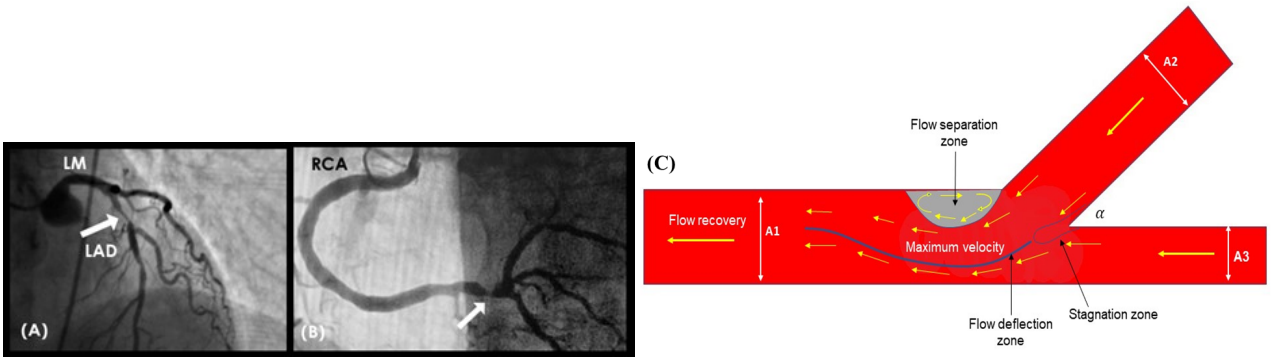

FIGURE 9. Lesions proximal to the bifurcation. (A) The lesion is proximal to the bifurcation angle, at the end of the proximal segment of the left anterior descending artery. This lesion could be formed from friction due to retrograde flow from the left anterior descending artery and from the diagonal. **(B)** This is the right coronary artery of an elderly man with a subtotal lesion proximal to the bifurcation with the PDA and posterior lateral branch (PLB). How did a lesion develop here and not at the origin of the PDA or PLB? In this case, the flow comes from a retrograde direction, the layers near the inner border recirculate and become turbulent due to differences in speed and friction. **(C)** In this model, the lesion is proximal to the bifurcation, the flow is retrograde and the turbulence is at the outer curve of the large main vessel.

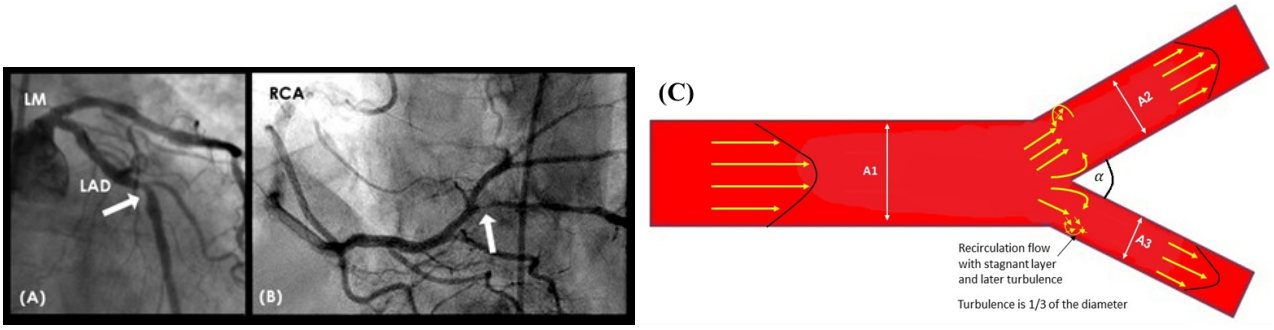

FIGURE 10. Lesions distal to the bifurcation (A) Lesion at the mid- segment, frequently seen at the bifurcation with obtuse marginals or diagonals. The main feature is that the lesion is distal to the origin of the side branch. This type of lesions is caused by separation flow with recirculating layers from an antegrade direction. **(B)** The lesion is distal to the bifurcation angle, at the ostium of the side. The mechanism of lesion here is speculated to be due to slow flow, from hypoperfusion, with the majority of the flow going to the main vessel. The flow comes from an antegrade direction. **(C)** In case of lesion distal to the bifurcation. the flow is antegrade and the recirculating flow is at the outer curve of a side branch.

$$\mathbf{Re} = \frac{\overline{\mathbf{V}}.\mathbf{D}.\boldsymbol{\rho}}{\boldsymbol{\mu}}$$

FIGURE 11. Reynolds Formula with V as velocity, D as diameter, ρ as the density of the fluid, and μ as viscosity. The Reynolds number (Re) helps predict flow patterns in different fluid flow situations. At low Reynolds numbers, flows tend to be dominated by laminar (sheet-like) flow, while at high Reynolds numbers, flows tend to be turbulent.

Hammer Shock from a Dynamic Coronary Perspective

In a similar setting, with the aorta as a tank and the coronary artery as a draining pipe, coronary blood moves forward during diastole. As the left ventricle (LV) (as a distal valve) contracts at the beginning of systole, coronary blood halts at the distal myocardial level. As time passes, the volume of stationary blood increases. At the same time, the LV contraction may squeeze the myocardial capillary network, forcing the stationary blood to move backward and slam against the anterograde flow at the transition from diastole to systole. This collision creates turbulence, rupturing any bubbles that may be present, injuring the intima, and beginning the atherosclerotic process. Based on the sequence of images outlining the collision, the event is in fact a water hammering shock, which happens at the mid segment of the RCA or distal end of the proximal segment of the LAD or LCX arteries, or in the iliac artery [13](12-15) (Figure 14A-H)

CAVITATION

In the practice of fluid mechanics, one of the most common problems damaging pumps and pipes is the cavitation phenomenon. Cavitation is defined as the formation of a vapor phase (i.e., vapor-filled cavities), which occurs when the dynamic fluid pressure decreases to a level lower than the vapor pressure of the gas diluted in the liquid. The lower dynamic pressure results in the formation and growth of vapor bubbles (referred to as “voids” in fluid mechanics engineering). As these bubbles are transported along the

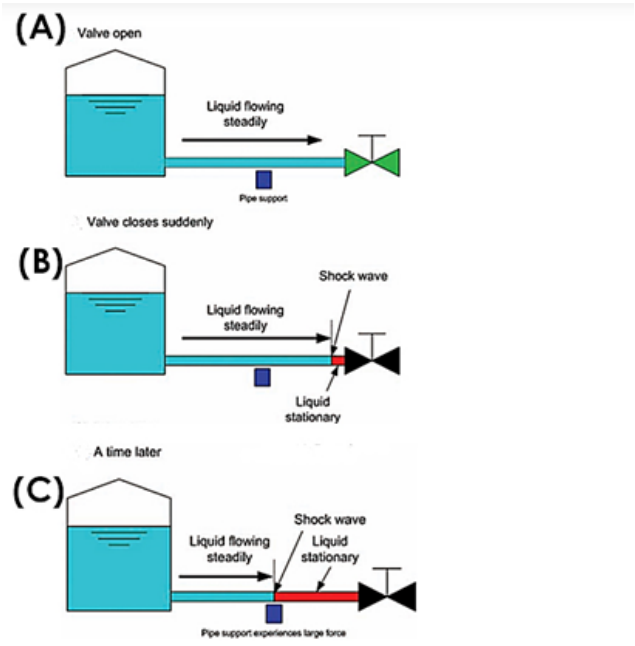

FIGURE 12. Fluid Mechanics of Collision (A-C). The sequence of antegrade and retrograde flows results in collision and shock waves when the distal valve of a pipe is abruptly closed. The above event is called the Water Hammer shock, which occurs when a valve is closed suddenly at the end of a pipeline system, power failure, main breaks, pump start-up, and shut-down operations, check-valve slam, rapid demand variation, opening and closing of fire hydrants, as a pressure wave propagates in the pipe, etc. [12]

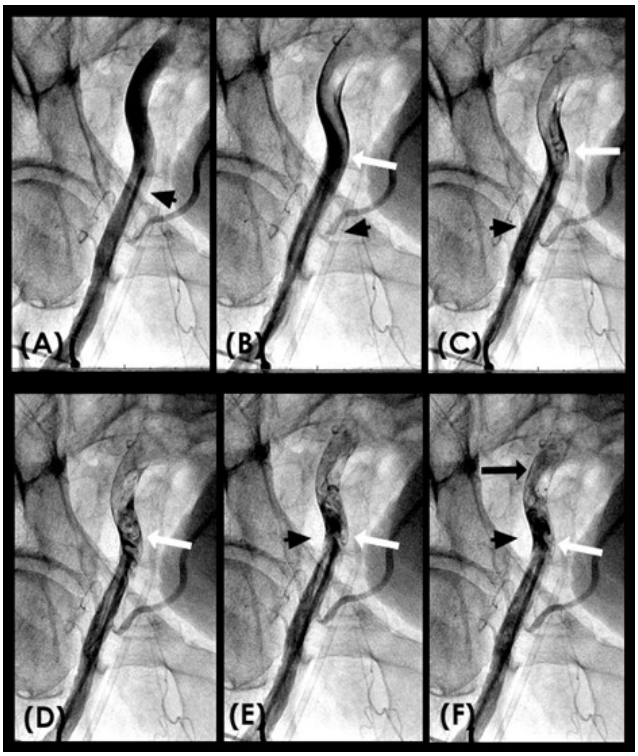

FIGURE 13. Vortex Formation and Turbulent Flow This is a series of 6 consecutive images of an iliac angiogram. **(A)** Contrast is injected into the iliac artery. **(B)** The blood in white is seen flowing in an antegrade direction, with a pointed tip of laminar flow curving along the apex of the iliac artery (white arrow). **(C)** The laminar blood flow stops abruptly, with all the layers recoiling on each other like a falling stack of dominoes (white arrow). **(D)** Now on the apical side of the iliac artery, the turbulence created by the halt of the antegrade flow becomes a large vortex which is a swirl of mixed blood and contrast similar to the cigarette smoke in the classic experiments of flow dynamics (white arrow). **(E and F)** The blood in white is disorganized with the mixing of blood in white and contrast in black. The blood, which is less viscous, occupies the apex of the curve (white arrow), while the more viscous contrast occupies a larger part of the inner curve (arrowhead). The enlarging size of contrast suggests the superior strength of the retrograde flow in this contest. The distal flow is being pushed back in a retrograde direction.

pipes, they will expand when flowing through a zone of low dynamic pressure due to the pressure difference between the vapor pressure inside them and the surrounding liquid. When they become sufficiently large, they become prone to rupture. In contrast, when flowing through the zones of high dynamic pressure, the bubbles will implode (Figure 15) [14]-[21](16-23).

Fluid Mechanics Perspective

In a setting of a long pipe with a valve in the middle, fluid will flow normally through the pipe if the valve is open and will stop if the valve is closed. In case of a long pipe in which the valve is abruptly closed, the fluid downstream to the valve will continue flowing, creating a growing vacuum that may cause the pipe to collapse or implode. This problem can be particularly acute if the pipe is on a downhill slope (Figure 16A-D). Furthermore, if the direction of the flow is reversed, the fluid in the retrograde direction may compress the vacuum (which is technically a void for engineers or a bubble for cardiologists). If the pressure is high enough, the vacuum (or void, or bubble) will explode, emitting micro-jets and damaging the wall of the pipe. This is a CAVITATION event [22].

Dynamic Coronary Flow Perspective

In a patient with a long posterior descending artery (PDA), the main lesion was at the ostium of the PDA, a commonly seen location. However, after stenting of the ostium of the PDA, with better flow, now a new mild lesion at the middle of the PDA appeared. Why and how could happen a lesion in the middle of a long PDA? With detailed inspection image by image of the flow in the PDA, it happened that the blood at the PDA continued to flow in an antegrade direction even the flow at the distal RCA prior to the PDA PLB bifurcation stopped. As the flow at the PDA continued to flow forward, it left a vacuum in the middle of the PDA. This was a void as called by fluid dynamics engineer or a bubble by radiologist or cardiologist. If the flow now reversed its direction, with enough pressure, an explosion could happen. In fact, it happened when the left ventricle contracted. It raised the systolic blood pressure, squeezed capillaries in the myocardium and reversed the direction of the flow to the proximal RCA. In this scenario, the blood from the distal PDA pushed backward and collided with the antegrade flow at the middle of the PDA, right at the location of the mild lesion. This is the imaging evidence of cavitation in coronary arteries or in any arteries

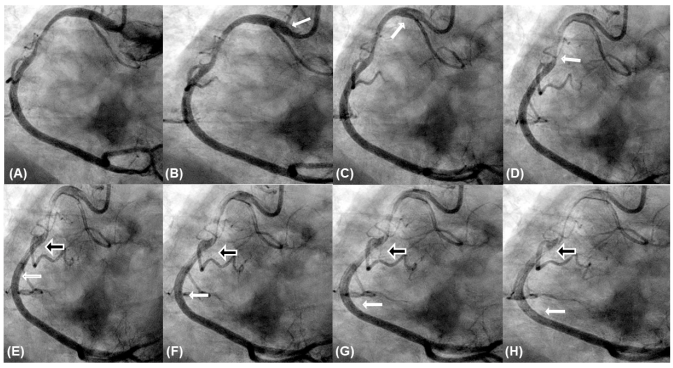

FIGURE 14. Collision in RCA (A-D). This is a series of 14 consecutive images of an angiogram of the right coronary artery (RCA) **(A)** The artery is completely filled with contrast. There is a mild lesion at the mid-segment (arrowhead). **(B)** The blood (white) is seen entering the ostium of the RCA (arrow). This is the beginning of diastole (first image of diastole). **(C)** The blood (white) is seen at the outer border of the first curve of the RCA (arrow). This is the second image of diastole. **(D)** The blood (white) is seen at the outer border of the proximal part of the mid-segment of the RCA (arrow). This is the 3rd image of diastole. **(E-H) Flow in Diastole and Collision during Transition to Systole. (E)** The blood (white) is seen following the outer border and arriving at the proximal part of the mid-segment of the RCA (arrow). This is the fourth image of diastole. **(F)** The blood is seen reaching the mid-segment of the RCA (arrow), where there is a mild lesion. This is the 5th image which marks the end of the diastole (arrow). This location is called the COLLISION LINE. Here the blood (white) is mixed with the contrast (black), seen as a random, disorganized black and white. This is the visual imaging of turbulent flow. **(G)** In this image, the contrast (black) concentrates at the mid-segment, at the collision line (black arrow). The contrast is also seen darker in the proximal part of the midsegment, compared with Figure 3. F above (arrowhead). This observation suggests the retrograde flow. The antegrade flow does not move much. This is the first image of systole. **(H)** The blood is seen reaching the beginning of the distal segment (arrow). This is the 2nd image of systole. The turbulent flow (mixing black contrast and white blood) is still seen prominently at the COLLISION SITE, and the retrograde flow of contrast (black) is seen to be lighter at the proximal part of the mid-segment (arrowhead).

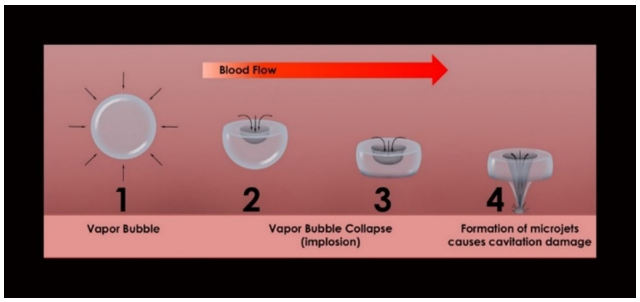

FIGURE 15. Bubble Formation and Implosion. As fluid flows through a pipe, bubbles form as the vapor pressure becomes higher than the dynamic pressure (1). When the bubbles enter areas of the pipes where the dynamic pressure increases above the vapor pressure, bubbles deform (2 and 3). With increasing dynamic pressure on the bubble, the surface tension of the bubble breaks and bursts, creating micro-jets (4).

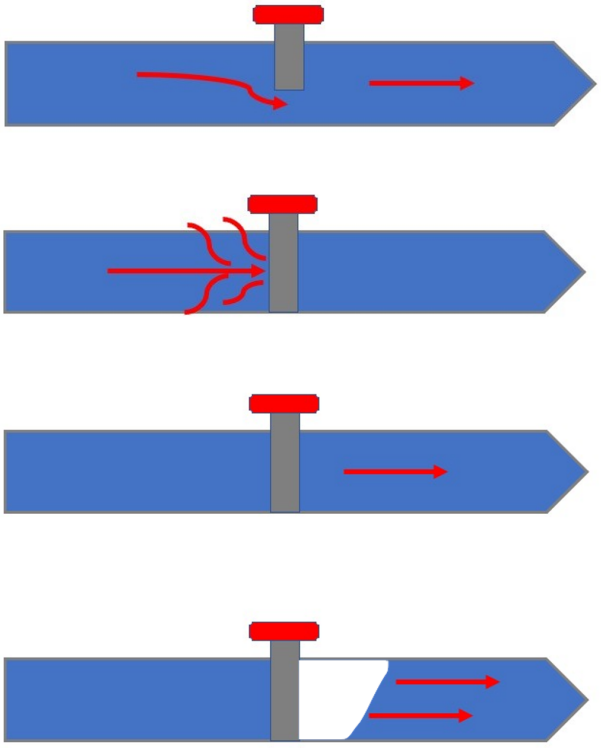

FIGURE 16. Cavitation. At the beginning, the fluid flows normally. Suddenly the flow is stopped in the middle by a lock; however, the flow distal to the lock continues to flow, leaving an empty area called a void in fluid mechanics terminology or a bubble in the artery. If the empty space continues to grow, the pipe can collapse or implode due to negative pressure. For any reason, if the fluid reverses its direction and slams into the void or bubble, the bubble with exploding. This is the cavitation phenomenon.

with similar setup. (Figures 17A-L)

Critical Thinking from Fluid Mechanics Perspective

In medicine, the alternating diastole and systole of the cardiac cycle is the fundamental truth. Nobody ever questions the productivity or safety of an anatomical design with sequential ventricular relaxation and contraction. In contrast, from a fluid mechanic perspective, a pump that stops and starts may not be the most efficient or safe. The "stop-and-start" flow at the aortic root may facilitate the formation of bubbles or vortices as a source for downstream cavitation (Figure 18) [14]. Could these "stops" and "starts" cause dilation and atherosclerotic changes in the aortic root?

CONCLUSION

Using a new technique of recording and reviewing CAGs, various types of flows such as laminar, turbulent, entrance flow, antegrade, and retrograde flow may be visualized and analyzed in detail during systole, diastole, collision, and recirculation. The most important images were those detailing the collision between antegrade and retrograde flow, resulting in water hammer shock or cavitation events that could potentially injure the intima and trigger the atherosclerotic process.

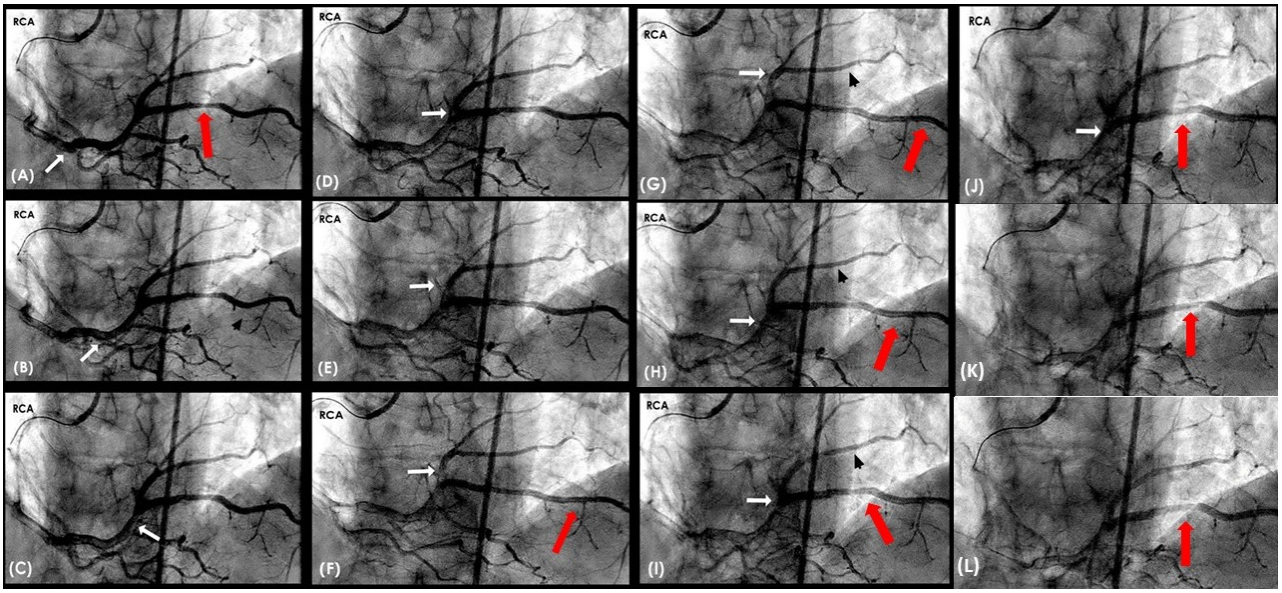

FIGURE 17. Cavitation in Coronary Arteries. This is a series of continuously sequential coronary images. The blood in white color arrived at the beginning of the distal segment (white arrow) of the right coronary artery (RCA), which was still covered by contrast. **(A)** At the posterior descending artery (PDA), the black contrast was still full. However, the mid-segment of the PDA was narrower with some white color of blood (red arrow). **(B)** The blood in white color now arrived at the middle of the distal segment of the RCA (white arrow). The flow at the PDA looked the same (black arrowhead). **(C)** The blood in white color now arrived almost at the bifurcation of the RCA and the PDA (white arrow). The flow at the PDA stayed the same. **(D) Flow at the Distal Segment.** The blood was now at the distal segment, past the origin of the PDA (arrow). The black contrast was still full at the proximal segment of the PDA. **(E)** The blood was now clearly distal to the origin of the PDA (arrow) while the contrast at the origin of the PDA stayed stagnant and homogenously black. **(F)** The blood (white) moved forwards into the PLB distal to the origin of the PDA (white arrow) while at the PDA, the blood was now clearly distal to the origin of the PDA while the contrast at the origin of the PDA stayed stagnant and homogenously black. The size of the distal PDA was smaller too. It was the sign of antegrade flow. (G) The blood in white color moved further in the antegrade direction (white arrow) at the PLB. The black contrast was still prominent at the proximal segment of the PDA however the blood in white color was seen moving further reaching and passing the origin of a small branch (seen as a vague white color streak. **(H) Collision with Prominent Retrograde Flow.** At the distal RCA, the contrast reversed its direction and flowed back past the origin of the PDA (white arrow). This is the site of COLLISION from a retrograde direction (arrow). It was a not passive collision from the antegrade direction. It was an active aggressive flow from distal-to-proximal direction. The flow at the distal PDA was seen reversing its direction, now on a retrograde direction. **(I) Collision at the Distal Segment.** At the distal RCA, **the contrast was pushed back** (white arrow) regaining 25% of the length of the artery conquered by the retrograde flow. At the PDA, the blood flow reversed back and the mid arterial segment looked bigger compared with the one in figure H (red arrow).Collision at the Distal Segment. **(J)** At the distal RCA, the contrast was pushed back (white arrow) regaining 25% of the length of the artery conquered by the retrograde flow. At the PDA, the blood flow reversed back and the mid arterial segment looked bigger compared with the one in figure H (red arrow). **(K, L)** At the distal RCA, the flow was antegrade again. At the PDA, the mid-segment was still full with blood in white color mixed with contrast. The border of this segment was un-organized due to injuries. This is the evidence of cavitation in coronary arteries.

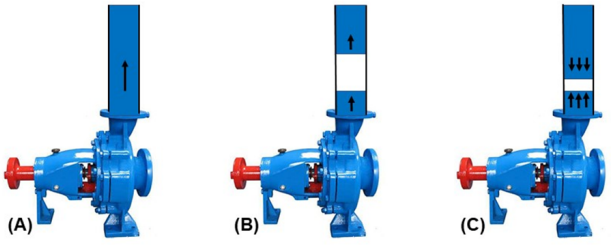

FIGURE 18. Cavitation if a pump keeps start and stop.

This new method of reviewing coronary flow dynamics and their anatomical correlations ushers in a new era of endless applications in the diagnosis and management of CAD, transient ischemic attack, stroke, peripheral arterial disease, critical limb ischemia, and other cardiovascular diseases.

CONFLICTS OF INTEREST

None of the authors have conflicts of interest to declare

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