Possible Benefits of Catheters With Lateral Holes in Coronary Thrombus Aspiration: A Computational Study for Different Clot Viscosities and Vacuum Pressures

Sajjad Soleimani, Gabriele Dubini, and Giancarlo Pennati

Laboratory of Biological Structure Mechanics, Department of Chemistry, Materials, and Chemical Engineering "Giulio Natta," Politecnico di Milano, Milan, Italy

The coronary arteries supply blood flow and oxygen to the heart tissues. If coronary blood flow is significantly hindered for an extended period of time, myocardial infarction may occur. A coronary artery can become progressively blocked by atherosclerotic plaque development (lasting years) or can be suddenly fully occluded (within a few seconds) by a thrombotic particle formed on the plaque surface or a plaque fragment due to erosion of vulnerable plaques. Atherosclerotic lesions can be treated surgically (coronary artery bypass grafting) as well as through drug therapies or percutaneous coronary interventions (balloon angioplasty and stenting) (1). Several methods are available to treat a coronary vessel blocked by a blood clot, mainly based on clot-dissolving medicines or on primary percutaneous coronary intervention (pPCI) using specific thrombectomy devices (2–4). In the former approach, pharmacological methods are used to fully dissolve the clot, whereas in the latter a very thin tube is guided toward the occluded vessel to mechanically remove the obstruction. Removal can occur according to different methods, including breaking down the clot and aspirating it. One of the most reliable methods is based on the simple usage of coronary aspiration catheters that remove the blood clot through pure application of vacuum pressure. This method has minimal clinical drawbacks and is highly effective (5). Recent studies have shown that manual clot aspiration before stenting may give improved clinical outcomes (6). Moreover, in selected patients undergoing

---

Received July 2013; revised November 2013.

Address correspondence and reprint requests to Dr. Sajjad Soleimani, Laboratory of Biological Structure Mechanics, Department of Chemistry, Materials, and Chemical Engineering "Giulio Natta," Politecnico di Milano, Piazza Leonardo da Vinci n.32, Milan 20133, Italy. E-mail: zzsajad@yahoo.com

pPCI, clot aspiration alone may be feasible and safe without additional balloon inflation or stent implantation (7). Thrombectomy devices may be manually activated or motorized. The former are usually composed of monorail catheters with a central lumen, which aspirate through one or more holes located at the tip. They are very simple to use, as manual aspiration is performed by means of a syringe connected to the catheter. Manual thrombectomy devices currently in use operate on similar principles but differ in terms of catheter material and aspiration lumen size, with potential differences in aspiration performance (5).

Although the clinical effectiveness of using aspiration catheters has been investigated in a number of clinical trials, reviewed by Costopoulos et al. (5), a systematic and quantitative comparison of catheter performances is still lacking. A few in vitro studies have evaluated the performances of commercial catheters during aspiration of simple fluids (distilled water or saline), gelatin (4), or actual blood clots (8,9) in setups replicating coronary (4,8) or cerebral arteries (9). Moreover, even fewer theoretical studies on thrombectomy devices exist, although the development of modeling strategies could be a useful tool to predict the aspiration performance of a specific catheter design.

Recently, our group (10) computationally studied the aspiration behavior of two catheter tips with and without lateral holes. A two-phase flow analysis was performed, where both blood and blood clot were modeled as Newtonian, immiscible fluids having different viscosities (the viscosity of clot was set at 10 times that of blood). Computational simulation suggested that the presence of additional holes, axially aligned on the upper side of the catheter, might not be effective (and might even be disadvantageous compared with a single central lumen) if the holes were not in contact with the clot. The two-phase flow approach was also adopted by Li et al. (11), who investigated the influence of clot age (simulated with different viscosity values) and catheter bending following the coronary artery curvature. As expected, older thrombi required longer aspiration times, whereas no role for catheter bending was found. A different modeling strategy for simulating clot aspiration was suggested by Romero et al. (12,13). A blood clot in a cerebral artery was modeled as a solid, cylindrically shaped element, physically interacting with the artery wall. Lumped parameter modeling was used both to mimic the elastoplastic clot behavior and the clot's adhesion to the vessel wall (spring-damper systems) and to account for the hemodynamic behavior during aspiration (flow resistance and inertia). The model was used to deduce the pressure necessary to extract blood clots of different length and mass from cerebral arteries in the posterior circulation of the brain.

In the current study we adopt a two-phase flow approach, similar to that of Pennati et al. (10) but using more sophisticated modeling: (i) non-Newtonian behavior was adopted for both blood and clot, based on experimental measurements on porcine blood clots; (ii) a surface tension was introduced to more realistically represent clot rheological behavior; and (iii) an image-based geometry was used for the coronary arteries.

The main aim of the current study is to find out how different aspiration catheters would perform (in terms of aspiration speed and complete aspiration success) when applied to remove clots of different viscosities. In particular, tips with different designs with regard to lateral holes are compared in a range of scenarios. To the best of our knowledge, only one commercial aspiration catheter, the Diver CE (Medtronic Invatec, Roncadelle, Italy) has adopted a multiple side hole approach, with a number of side holes in addition to the main central lumen. In fact, among Diver CE products, two catheter designs are available: with or without side holes for fresh and organized clots, respectively. In the more recent design, two holes are located on the lateral parts of the head close to the beak in a symmetrical configuration (5), while in a previous design (14), three holes were created along a line on the opposite side of the beak on the head of the catheter. While the performance of the older design was previously investigated (10), the current study focuses on the behavior of catheters with side holes in the lateral parts of the tip, similar to the Diver CE Max. Different conceptual designs are compared for different clot rheological properties and vacuum pressures, providing insight into the aspiration behaviors.

MATERIALS AND METHODS

A finite-volume fluid dynamics model was developed to simulate the aspiration of a clot from an occluded vessel. A two-phase flow approach was adopted, considering both blood and clot as immiscible fluids with different rheological properties (10). The model includes a coronary aspiration catheter, a coronary artery tract, and blood volume with a bulk of clot (Fig. 1).

Model geometry

For the aspiration catheter, only the distal portion was modeled. A beveled tip (or shaped like a

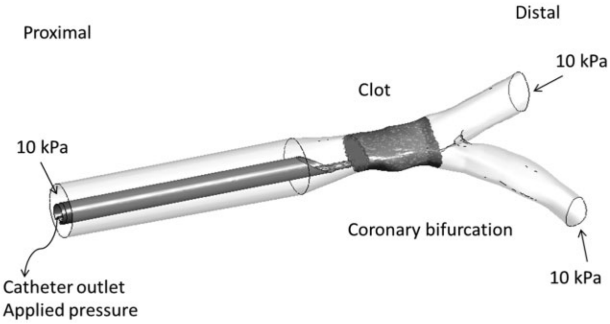

FIG. 1. The image-based model showing the left main coronary artery segment and the inserted catheter close to the bulk of the clot.

beak) was assumed, having an external diameter of 1.72 mm, with the lumen partially occupied by the cylindrical guide wire so that the internal area of the cross-section was 1.5 mm^2 (Fig. 2). This geometry, although generic, is representative of most commercially available catheters (5).

In this study, different catheter tip designs with additional holes located on the lateral part of the head of the tip were investigated. Six combinations were studied, with holes on the upper side, the lower side, or both sides with respect to the beak of the tip, and all were designed symmetrically. Two different sizes were considered for the holes (radius of 0.375 or 0.25 mm).

The catheter model was inserted into a model of a bifurcated segment of the main left coronary artery, near a totally occlusive clot (Fig. 1). The adopted coronary model (courtesy of the European Bifurcation Club, Lisbon, 2011) was reconstructed via the method based on fusing intravascular ultrasound and computed tomography techniques described by Giessen et al. (15). A cylindrical extension of the main branch of the coronary was done to create a model region around the catheter tip, whereas the two daughter branches were cut in order to reduce computational expenses.

The coronary was blocked by a clot (volume of about 50 mm^3) located close to the bifurcation. The tip of the catheter was located 1 mm away from the bulk of the clot. This was in agreement with the advice to keep the tip a few millimeters away from the clot in order to prevent embolization (13), which was also recommended by the Medtronic Invatec Diver CE manual.

Fluid rheology

A Bird–Carreau model was adopted to describe the non-Newtonian viscosity of blood (16,17):

$$\mu = \mu_\infty + (\mu_0 - \mu_\infty)\left(1+\lambda^2\dot{\gamma}^2\right)^{\frac{n-1}{2}}$$

where $\mu_0 = 0.56$ Pa·s, $\mu_\infty = 0.0345$ Pa·s, $\lambda = 3.313$ s, and $n = 0.3568$.

The clot viscosity was measured in previous experiments performed on clot specimens obtained from porcine blood (18). An oscillatory shear rheometer with plate–plate geometry was used to measure the rheological properties of clots. A number of dynamic frequency sweep tests were performed. As a first step, the blood sample was exposed to a dynamic rotation with adequate oscillatory frequencies and resting times (Table 1) to produce different clots ("fresh" and "organized" clots) categorized as low,

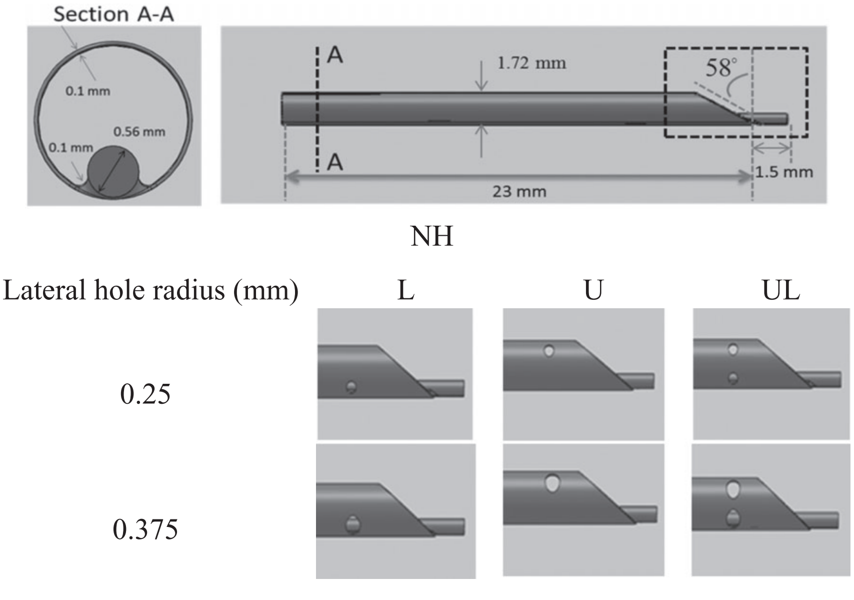

FIG. 2. Geometries adopted for the tip of the coronary aspiration catheter. Main dimensions are shown for the tip with a single central lumen (no holes, NH, top panel). Six conceptual hole designs are considered (bottom panel), where U and L indicate the lateral hole locations (upper or lower side, respectively), and 0.375 and 0.25 indicate the radius size of the hole in mm.

TABLE 1. *Viscosity coefficients of three clots of porcine blood*

Case	Resting time (s)	Oscillatory frequency used during resting time (Hz)	*A*	*B*
Low viscosity	1000	1	21.45	0.8866
Medium viscosity	1000	0.5	34.14	0.9188
High viscosity	2000	0.05	98.65	0.9552

medium, or high viscosity. Then, in order to measure the rheology of the clots obtained, a dynamic frequency sweep measurement was performed. Each sample was exposed to a maximum shear strain of 0.3% and different angular frequencies (range 0.1 to 100 rad/s), and the complex dynamic viscosity of the thrombus was measured.

Thrombus rheology was then described by a non-Newtonian power law:

$$\mu = A\dot{\gamma}^{(-B)}$$

where A and B are coefficients, reported in Table 1 for three different clots showing different viscosities. Rheological models adopted for clot and blood are shown in Fig. 3.

Moreover, surface tension was introduced to better model clot response during aspiration. In the literature, a value of about 0.05 N/m is suggested for the surface tension of blood (19). A value three times larger was adopted in this study to mimic the clot's capability to withstand tension and remain cohesive during catheter aspiration. In the real world, this capability is mainly derived from the fibrin network within the thrombus. In our modeling, the surface tension was introduced to more realistically model this characteristic. The selected value of the surface tension was obtained from a preliminary sensitivity analysis (briefly reported here) where the surface tension of the thrombus was progressively increased for the UL-0.375 catheter geometry (holes 0.375 mm in radius on both upper and lower parts). The analysis showed that the thrombus fragments excessively and assumes an unrealistic shape at low surface tension (from 0 to 0.05 N/m), with the mass being aspirated only from the central region of the thrombus. At a larger value (0.15 N/m), the thrombus remains more cohesive, although fragmentation is still present. The same behavior was observed at 0.25 N/m surface tension. For these reasons, we decided to use a value of 0.15 N/m for the blood clot.

Computational fluid dynamics simulations

The reconstructed coronary geometry was merged with the investigated catheter design model, and the whole model was meshed using ANSYS ICEM CFD 12.1 (ANSYS, Inc., Canonsburg, PA, USA) for computational fluid dynamics simulations. To investigate the aspiration performance of the catheters, a number of transient simulations were performed, applying pressure boundary conditions at the four model outlets (catheter, main coronary, and daughter branches of the coronary). The movement and aspiration of the clot is due to the pressure difference between the catheter outlet and the other model boundaries. Blood and clot were assumed to be initially stationary (zero velocity throughout the model), and for the sake of simplicity, fixed pressures were maintained during the simulation. Due to the long length of the catheter, the pressure applied through the syringe is reduced to a much lower value at the tip of the catheter. To mimic different conditions, two pressure values, −10 and −30 kPa (−75 and −225 mm Hg) were applied at the catheter outlet to simulate different vacuums. In accordance with the assumption of initially stationary fluids in the coronary vessel due to the blockage caused by the clot, an identical pressure value (10 kPa or 75 mm Hg) was assumed at all the vessel boundaries (10).

The transient computational analyses were carried out by means of ANSYS Fluent to characterize the clot movement and aspiration. Firstly, grid and time-step sensitivities were tested to ensure the reliability of the computational model. Specifically, a parameter related to aspiration performance was adopted as controlled variable: the aspirated clot mass. First, the mesh density was progressively increased so that when the number of elements was increased five times, the quantities changed by less than 3%. Then, the time step was progressively reduced so that when

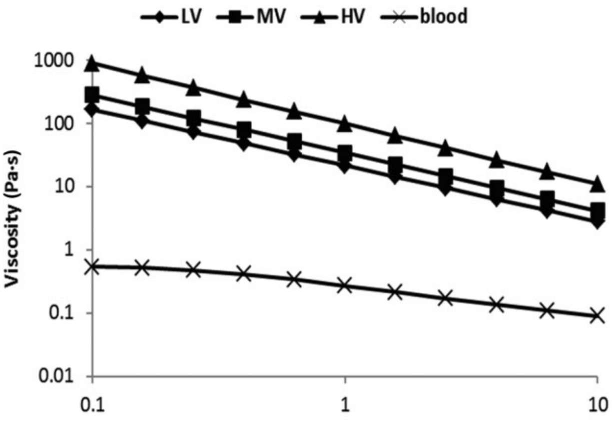

FIG. 3. Viscosities of blood and three clot samples (low viscosity, LV; medium viscosity, MV; and high viscosity, HV) versus shear rate.

TABLE 2. *Adopted parameters in the simulations of clot aspiration*

Simulation	Catheter geometry	Clot viscosity	Pressure difference (kPa)
1	L-0.25	Low	20
2	L-0.375	Low	20
3	U-0.25	Low	20
4	U-0.375	Low	20
5	UL-0.25	Low	20
6	UL-0.375	Low	20
7	NH	Low	20
8	NH	Medium	20
9	UL-0.375	Medium	20
10	NH	High	20
11	UL-0.375	High	20
12	NH	Low	40
13	UL-0.375	Low	40
14	NH	Medium	40
15	UL-0.375	Medium	40
16	NH	High	40
17	UL-0.375	High	40

L, holes in lower part; U, holes in upper part; UL, holes in both upper and lower part; NH, no holes; 0.25 and 0.375, radius of holes (mm).

it was reduced 10 times, the quantities changed by less than 3%. According to the sensitivity analysis, a final mesh of 1 011 000 elements and a time step of 0.01 s were adopted for the simulations. The sensitivity analysis was performed for a single condition and assumed to be valid for all other configurations. In particular, the UL-0.375 catheter geometry was used, and the case with the lowest clot viscosity and the highest vacuum was considered. The UL-0.375 geometry was expected to be the most critical geometry, as the presence of a main central entrance plus four lateral holes of a large size causes a higher level of flow pattern distortion and a strong interaction of streamlines entering the catheter through the various entrances.

Two sets of simulations were performed in order to investigate the role of lateral hole design in aspirating clots with various viscosity values and applied vacuum pressures (Table 2). First, the role of hole design in aspiration of the clot was investigated, considering the lowest-viscosity clot and low vacuum pressure (simulations 1–7). Then, the best-performing hole design for such conditions of low clot viscosity and low vacuum pressure was compared with a generic catheter with no lateral hole (NH) for a range of values of viscosity and pressure (simulations 8–17). The results are shown in the form of aspirated clot mass percentage over time period evaluated at the catheter outlet section.

RESULTS

A qualitative analysis of clot movement over time suggests typical aspiration dynamics. Two examples (NH and UL-0.375 catheter designs) of low viscosity clot aspiration, with application of a pressure difference of 20 kPa, are illustrated in Fig. 4. Initially, the clot gradually moves from its initial position and

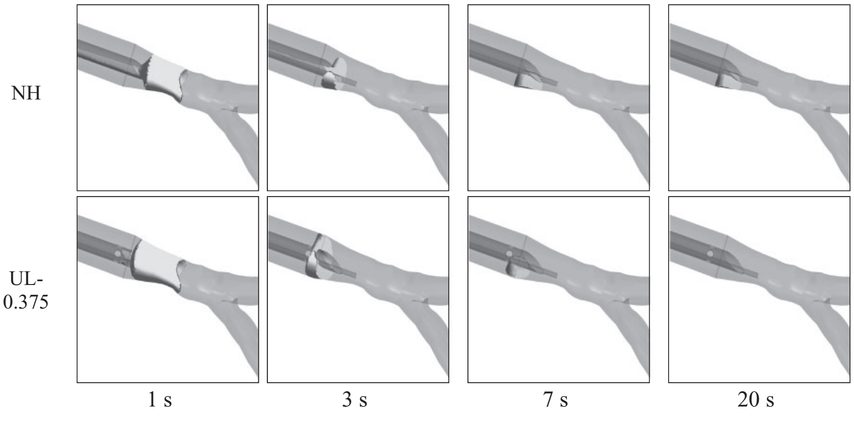

FIG. 4. Simulation results of catheter aspiration for a clot with low viscosity and a pressure vacuum of –10 kPa (i.e., pressure difference of 20 kPa). A sequence of various phases of clot aspiration is depicted for a single-lumen catheter (NH) and for a catheter with additional lateral holes (UL-0.375).

partially crosses the catheter tip (Fig. 4, first panels, after 1 s of aspiration); then, it is aspirated very quickly, and the main bulk of the clot enters the catheter (Fig. 4, second panels, after 3 s of aspiration). Eventually, the aspiration speed radically slows down, as the clot fragments become entrapped between the catheter wall and vessel wall due to tip–clot interaction (Fig. 4, third panels, after 7 s of aspiration). Simulation at the first 20 s of aspiration (Fig. 4, fourth panels) demonstrates that in the case of a single catheter lumen (NH design), clot fragmentation hinders a complete clot aspiration, whereas in the case of the UL-0.375 design, the entrapped clot can be aspirated thanks to the additional lateral holes.

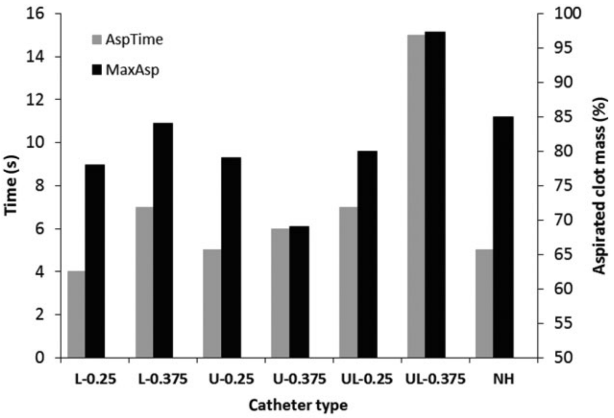

FIG. 6. Aspiration performances of the catheter designs based on the quantitative parameters AspTime and MaxAsp.

Effect of lateral holes on catheter aspiration ability

Figure 5 provides a quantitative comparison of the seven investigated catheter designs, plotting the aspirated clot mass versus time for low viscosity and 20 kPa of pressure difference. All the curves confirmed the previously described behavior, showing rapid initial aspiration followed by a very slow aspiration when, virtually, a maximum aspirated clot mass is obtained (corresponding to the curve asymptote). However, from a quantitative point of view, different designs with regard to the holes produced quite different results. For instance, the designs aspirated different clot masses after 30 s, with a single design (UL-0.375) allowing a complete aspiration.

Hence, the aspiration performance of different types of catheter may be compared in terms of essential time to reach an asymptotic value of degree of aspiration and aspirated clot mass. In order to effectively compare the different curves and assess the catheter aspiration performance, two quantitative parameters were defined: AspTime, the time to reach the maximum degree of aspiration, that is, the time period after which the aspiration rate is very low (e.g., curve slope ≤0.6%/s—the curve slope was measured after smoothing the curve so that the interpolation between the simulated time points could be achieved); and MaxAsp, the corresponding aspirated clot mass, expressed as a percentage of the original clot mass. Obviously, lower values of the former coupled to higher values of the latter indicate good catheter performance.

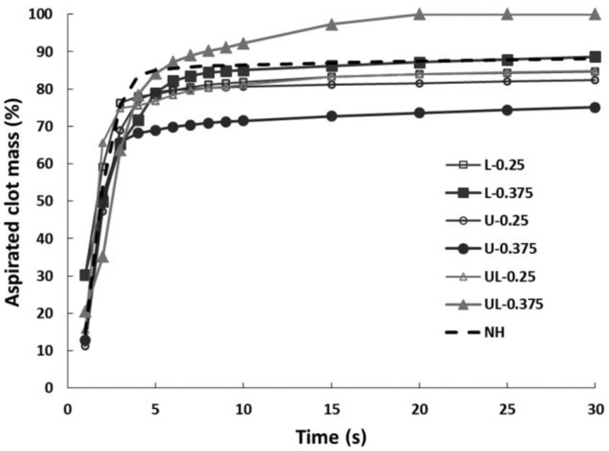

FIG. 5. Aspirated clot mass for each aspiration catheter design for low clot viscosity and pressure difference of 20 kPa.

These quantities are shown in Fig. 6 for low clot viscosity and a pressure difference of 20 kPa. Figures 5 and 6 show the influence of hole design on the performance of the aspiration catheter for fixed clot viscosity and vacuum pressure. The behavior of the NH catheter was considered as a control for the performance of catheters with additional lateral holes.

The holes designed into the lateral aspect of the catheters differed in size (radius of 0.25 or 0.375 mm), number (one or two), and location (upper, lower, or both). The catheters with smaller holes provided lower aspiration ability when compared with NH, regardless of hole location and number. In contrast, the catheters with larger holes exhibited different performances compared with NH, depending on hole number and location. For example, the U-0.375 (upper holes 0.375 mm in radius) and UL-0.375 had the worst and best aspiration ability, respectively, among all the combinations of hole designs shown in Fig. 5.

Despite permitting complete aspiration, UL-0.375 required the highest AspTime. However, taking into account the low values of AspTime (lower than 15 s for all the hole combinations), the AspTime differences among the investigated catheter designs shown in Fig. 6 may be considered trivial from a clinical point of view. Accordingly, the positive aspect of the UL-0.375 design (highest MaxAsp) is more important than the negative aspect (highest AspTime). All other hole combinations had similar or lower aspiration ability compared with the NH design. It should be also considered that the NH design did not achieve a complete aspiration.

The UL-0.375 design was then identified as the best catheter for low viscosity and low vacuum pressure and further investigated based on different scenarios: fresh clot (low viscosity) versus more organized clot (medium and high viscosity) and low vacuum pressure versus high vacuum pressure (see Table 2).

Efficacy of lateral holes for different vacuum pressures and clot viscosities

The performances of the UL-0.375 and NH catheters for various clot viscosities (low, medium, and high) as well as aspiration pressures of 20 and 40 kPa are compared in Figs. 7 and 8. Above, we observed that at low pressure (20 kPa) and low clot viscosity, the UL-0.375 catheter had the best performance. This trend, however, completely reversed at both medium and high viscosities and at 20 kPa. Moreover, at the highest investigated viscosity, the UL-0.375 catheter failed to aspirate any portion of the clot (no aspiration after 120 s).

The catheter with the NH design had shorter AspTime for various clot viscosities and aspiration pressures. Although this effect was negligible for the aspiration of clots with low viscosity, in aspiration of clots with higher viscosity and at lower pressure this parameter could become critical, as it affects the duration of pPCI.

It is also worth noting that the application of a higher aspiration pressure (40 kPa) reduced the differences between the two catheter designs and presented lower risk of aspiration failure. Nevertheless, at high clot viscosity, the NH design aspirated better than the UL-0.375.

DISCUSSION

In the current study, a two-phase flow approach was adopted to computationally evaluate the aspiration performance of catheters applied to remove coronary thrombi (blood clots) of different viscosities. In particular, possible benefits of using tips with lateral holes in addition to a central lumen were assessed. Although a number of trial studies have been done considering the pros and cons of thrombectomy devices (1,5,20), a specific study

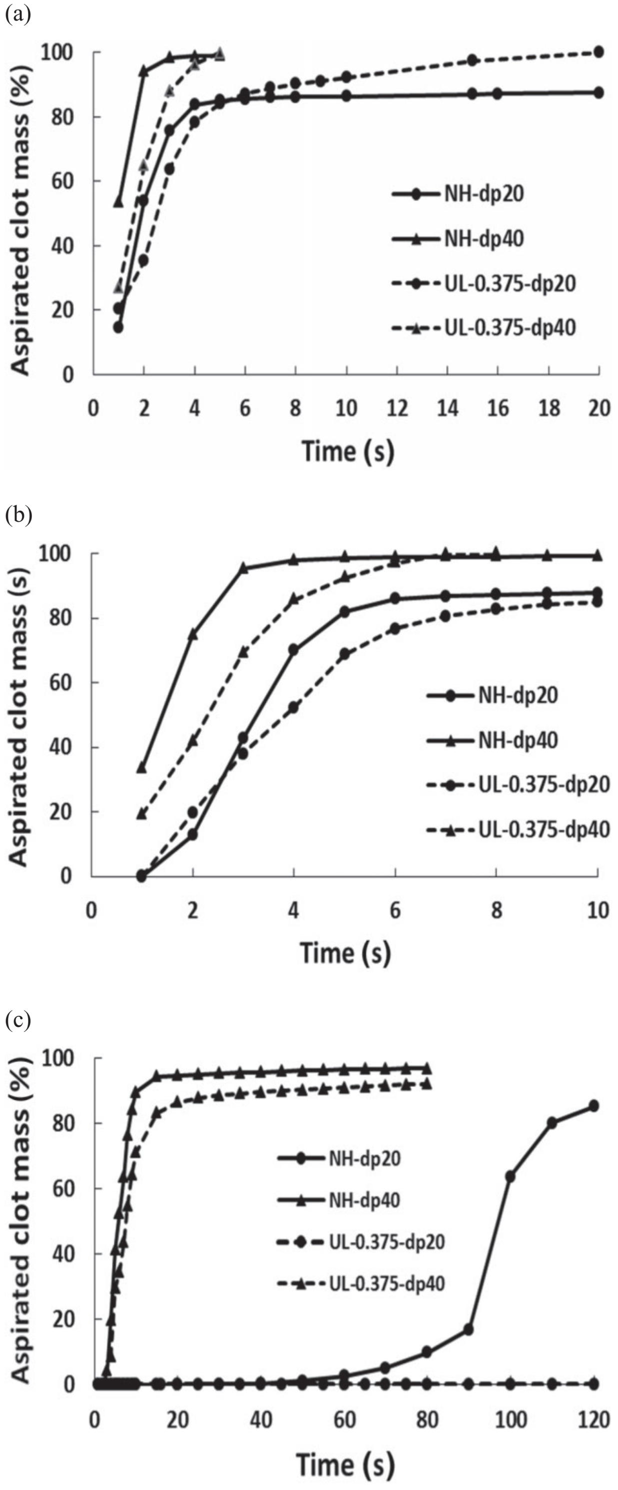

FIG. 7. Aspiration of clot mass via NH and UL-0.375 catheters for pressure differences of 20 and 40 kPa and clots of different viscosity values: (a) low, (b) medium, (c) high.

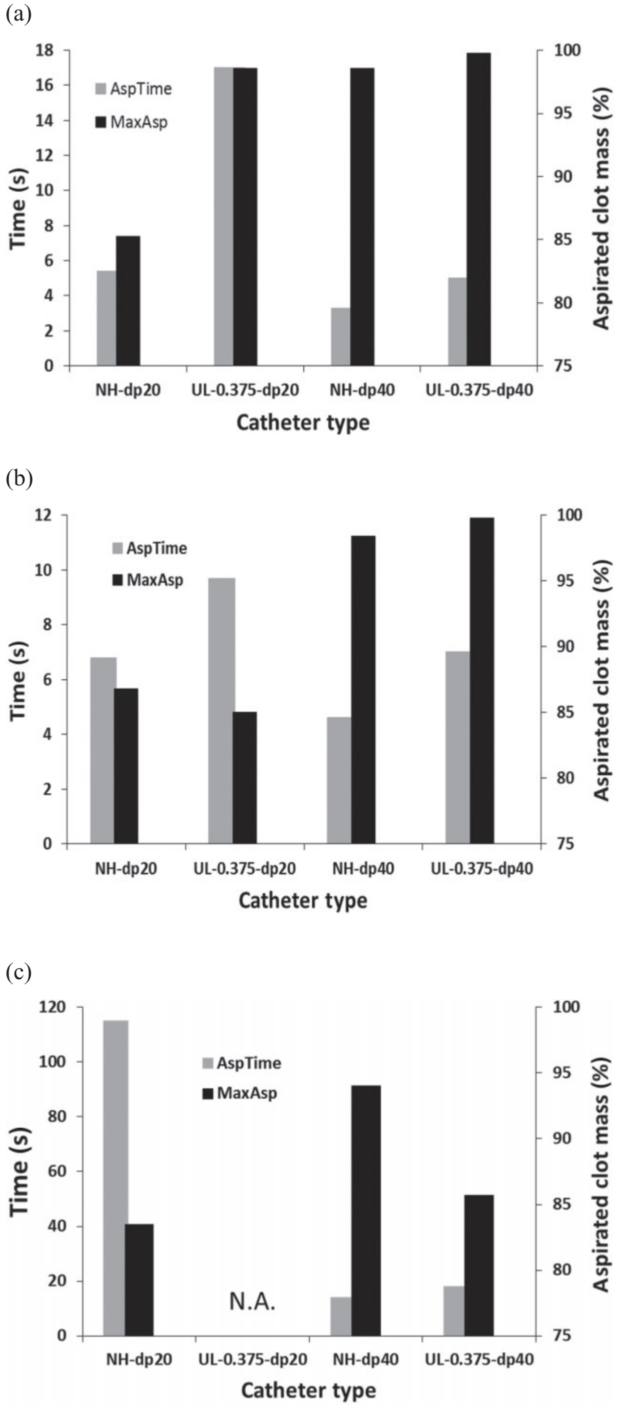

FIG. 8. Comparison of the aspiration performance of catheters with (UL-0.375) and without (NH) lateral holes at different applied pressures according to AspTime and MaxAsp for (a) low-, (b) medium-, and (c) high-viscosity clots. N.A., data not available, as the simulation was stopped at 120 s and no blood clot mass had yet been aspirated.

investigating the role of tip geometry in aspiration of clots with different properties and at different applied pressures is lacking. The two-phase flow strategy applied to the study of clot aspiration (i.e., considering both blood and blood clot as fluids) was originally suggested by Pennati et al. (10). The two-phase flow approach allowed the authors to study the performances of catheters with multiple aspirating lumens (central lumen plus lateral holes), as the clot may fragment and follow various paths. In contrast, this was not possible for Romero et al. (12), who exploited an analytical approach to model the aspiration via a mechanical thrombectomy device, as the clot was described as a solid block. Nevertheless, in the current analysis, the two-phase flow approach was significantly improved to describe clot aspiration through the catheter in a more realistic way. The assumption of Newtonian fluid viscosities was replaced here with improved rheological models for blood (16,17) and clot (power law) behaviors. Three different power laws simulating different blood clot ages were used based on experimental measurements. The considered viscosities show values up to three orders of magnitude greater than blood viscosity, whereas in the previous study (10), a single, quite low value of clot viscosity (10 times that of blood viscosity) was simulated. The use of a very low viscosity, corresponding to an extremely fresh blood clot, caused a very fast aspiration (0.1 s was enough to aspirate a large quantity of clot), limiting the realism of the model and its applicability to clinical cases. Indeed, usually at least 2 h pass between symptom onset (i.e., chest pain) in a patient and the pPCI (21,22), leading to higher clot viscosities. The aspiration times obtained in the current study ranged from a few seconds to a few minutes, depending on viscosity and aspiration pressure. These values are in accordance with the literature, although the only reported data found refer to a different condition (12,23).

Moreover, in the current study, the rheological model of the blood clot included the effect of surface tension. The presence of surface tension is important, as it affects the interaction of the clot with the vessel wall as well as its resistance to fragmentation. In fact, a coronary blood clot can be highly friable or able to sustain tensile forces, according to its composition. Specifically, the content of fibrin, which is highly variable and associated with the time after ischemia, is expected to play an important role in the clot's tensile resistance (21,22). A preliminary computational study (24) indicated that simulated clot behavior changes when surface tension is introduced in the model, although the main effect on aspiration is produced by the viscosity. For the sake of simplicity, a single value of surface tension was considered in the current study; it was assumed to be three times the value suggested for the blood (19) to enhance the clot cohesion during catheter aspiration. As a future study, a purposely designed investigation could be carried out to associate specific values of surface tension with blood clot composition.

The relative position of clot and catheter tip is important with regard to the presence of lateral holes, as it was previously demonstrated that holes far from the clot preferentially aspirate blood and may hinder the percutaneous treatment (10). In the current study, a gap (1 mm) existed between the tip and the clot mass, whereas in previous studies done by Pennati et al. (10), the catheter tip was immersed within the blood clot. The configuration adopted in this study seems to be more realistic, as it is often recommended not to push the thrombus to prevent embolization (13). Although in all tip configurations investigated in the current study the lateral holes were initially far from the clot mass, the computational results indicated that the exact location of the hole is a critical parameter for effective aspiration of the clot. The first set of simulations suggested the tip design with two larger holes (UL-0.375 model) as the best-performing. This was due to a combination of larger aspirating area and good hole location. Indeed, a mere increase in hole area is not sufficient to increase the aspirated clot mass, as clearly proven by comparing the performance of the U-0.25 and U-0.375 designs (MaxAsp 78% and 69%, respectively), as shown in Fig. 6. Nevertheless, the results shown in the same figure evidenced an opposite trend for the holes located in the lower part of the catheter (MaxAsp 77% vs. 84% for L-0.25 and L-0.375, respectively). Generally, it seems that tips with holes in the lower part performed better than those with holes in the upper part. This observation is likely associated with tip shape. In fact, most commercial aspiration catheters for coronary thrombus are produced with a beveled tip in order to provide an easier insertion of the catheter into the vessel. Due to this specific shape, when a blood clot fragments due to its interaction with the tip, a portion may get trapped between the catheter and the vessel wall. This mainly occurs in the lower part of the catheter tip. Hence, if the additional holes are located on the lower part of the catheter close to the beak, they will enhance the catheter performance. In contrast, a design with holes only on the upper side of the catheter does not improve the effectiveness of aspiration as the vacuum pressure is used to aspirate blood instead of clot, also weakening the aspiration performance of the central lumen. This explains why larger holes located in an area where the clot is less likely to become trapped during aspiration (upper part) are detrimental.

Although the hole design plays a great role in the aspiration performance, possible advantages in using additional lateral holes in the aspiration catheter clearly depend on the viscosity of the clot and, partially, on the applied aspiration pressure (second set of simulations). Figure 8 shows opposite behaviors for low and high clot viscosity at a fixed pressure difference (20 kPa). At low viscosity (Fig. 8a), the catheter with lateral holes (UL-0.375) allowed a complete aspiration of the clot (in a few seconds right after AspTime), whereas the single-lumen catheter (NH) aspirated about 85% (MaxAsp). Conversely, for the high-viscosity blood clot (Fig. 8c), the UL-0.375 design failed to aspirate the blood clot (no aspiration after 120 s), while the NH catheter aspirated 84% of clot mass (MaxAsp). For an intermediate viscosity (Fig. 8b), the performances of the two designs were quite similar (MaxAsp 85% and 87% for UL-0.375 and NH, respectively). These contrasting performances can be explained by looking at aspiration dynamics and considering the presence of two fluids with quite different viscosities. As already observed, the lateral holes and the main central lumen act in parallel to aspirate the surrounding fluids. Hence, when a catheter entrance is located far from the blood clot, it preferentially aspirates blood (the fluid with lower viscosity) instead of blood clot. For a high-viscosity clot this effect is increased; thus, it is preferable to have a single aspirating lumen (the central one) as close as possible to the blood clot. Conversely, when the viscosity of the clot is closer to the blood viscosity (low-viscosity cases), the two fluids move together towards the catheter tip, and the presence of additional, well-located lateral holes prevents the clot becoming trapped (as described above).

Compared to the other investigated parameters (hole features and clot viscosity), the influence of the aspiration pressure is more straightforward: an increase in the aspiration pressure increases the aspirated clot mass and reduces the aspiration time. Generally speaking, at higher aspiration pressures, the differences between catheters with and without lateral holes, as well as the effects of viscosity, are reduced.

The main findings of this computational analysis are in agreement with those reported by Pennati et al. (10), who compared two designs of a commercial catheter (Medtronic Invatec), one with a single central lumen and one with additional lateral holes. The lateral holes were all placed along a line on the upper wall of the tip, and the authors concluded that this specific design of side holes tended to aspirate blood rather than clot, reducing the aspiration performance. It is worth noting that the catheter producer recently modified the device concept, moving the side holes from the upper part of the tip to the two lateral parts of the wall of the tip at the lower side (5,14) and also decreasing the number of holes (from three to two). This new design strategy finds a rationale in our results. Similarly, the clinical indications of the two catheter designs—with lateral hole for a fresh clot (i.e., low viscosity) or without lateral holes for an organized clot (i.e., high viscosity)—are now understandable.

Although the exact relationship between the parameters investigated in the current study and possible clinical adverse events is difficult to establish, some considerations can be made.

The most important adverse event that may occur following percutaneous coronary intervention is coronary reembolization. This may happen if aspiration is incomplete and, consequently, small pieces of clot remain in the bloodstream, with possible acute myocardial infarction of downstream tissues. The current computational results suggest that, in order to obtain better aspiration performance and reduce the risk of reembolization, the catheter geometry should be adapted according to the features of the thrombus.

Despite the good correspondence of the current results with other data, a number of limitations of the adopted model can be listed, without affecting the general conclusion of the study. First, a generic beveled tip was used here, while the commercial catheter devices may have more complex shapes (5). The obtained results are representative of most commercial catheter behaviors, although the quantitative parameters could be different according to different beveled tip shapes. Furthermore, to reduce the computational time, only the tip portion of the catheter was modeled, and a reasonable vacuum pressure at the tip was assumed, as deduced from preliminary in vitro experiments on commercial catheters (25). Catheter shafts with different lengths and lumens (size and shape) (5) could create different pressure drops, changing the vacuum pressure at the tip. Moreover, the applied vacuum pressure was assumed fixed in time, whereas in reality it falls during the aspiration phase due to syringe filling. Finally, a clot bulk with a volume of about 50 mm^3 was assumed, although longer thrombi can occur in the coronary tree. The observed aspiration trends are expected to be valid for higher clot volumes as well, with merely an increase in the time of aspiration (18).

CONCLUSION

This computational analysis shows that the use of additional lateral holes in aspiration catheters provides beneficial effects only for low-viscosity thrombus, whereas when the thrombus viscosity increases, the single-lumen catheters are likely to perform better.

Acknowledgment: This research is funded by the European Commission through MeDDiCA ITN (grant agreement PITN-GA-2009–238113).

Conflict of Interest: The authors report no conflict of interest.

REFERENCES

1. Svilaas T, Vlaar PJ, Horst IC, et al. Thrombus aspiration during primary percutaneous coronary intervention. *N Engl J Med* 2008;358:557–67.
2. Caceres M, Weiman DS. Optimal timing of coronary artery bypass grafting in acute myocardial infarction. *Ann Thorac Surg* 2013;95:365–72.
3. Rioufol G, Collin B, Vincent-Martin M, et al. Large tube section is the key to successful coronary thrombus aspiration: findings of a standardized bench test. *Catheter Cardiovasc Interv* 2006;67:254–7.
4. Sakurada M, Ikari Y, Isshiki T. Improved performance of a new thrombus aspiration catheter: outcomes from in vitro experiments and a case presentation. *Catheter Cardiovasc Interv* 2004;63:299–306.
5. Costopoulos C, Gorog DA, Di Mario C, Kukreja N. Use of thrombectomy devices in primary percutaneous coronary intervention: a systematic review and meta-analysis. *Int J Cardiol* 2013;163:229–41.
6. De Luca G, Dudek D, Sardella G, Marino P, Chevalier B, Zijlstra F. Adjunctive manual thrombectomy improves myocardial perfusion and mortality in patients undergoing primary percutaneous coronary intervention for ST-elevation myocardial infarction: a meta-analysis of randomized trials. *Eur Heart J* 2008;29:3002–10.
7. Kramer MC, Verouden NC, Li X, et al. Thrombus aspiration alone during primary percutaneous coronary intervention as definitive treatment in acute ST-elevation myocardial infarction. *Catheter Cardiovasc Interv* 2012;79:860–7.
8. Hara H, Nakamura M, Komatsu H, et al. Comparison of the in vitro performance of 6 and 7 French aspiration catheters. *EuroIntervention* 2007;2:487–92.
9. Tennuci C, Pearce G, Wong J, et al. Comparison of the effectiveness of three methods of recanalization in a model of the middle cerebral artery: thrombus aspiration via a 4F catheter, thrombus aspiration via the GP thromboaspiration device, and mechanical thrombectomy using the Solitaire thrombectomy device. *Stroke Res Treat* 2011;2011:186424.
10. Pennati G, Balossino R, Dubini G, Migliavacca F. Numerical simulation of thrombus aspiration in two realistic models of catheter tips. *Artif Organs* 2010;34:301–10.
11. Li Y, Nallamothu RK, Rafiroiu D, et al. CFD analysis study on the impact of the coronary anatomy on the efficiency of the coronary thrombectomy: the effect of bend angles. *IFMBE Proc Meditech* 2011;36:306–9.
12. Romero G, Martinez M, Pearce G, Mera M. An investigation into the performance of a new mechanical thrombectomy device using bond graph modeling: application to the extraction of blood clots in the middle cerebral artery. *Simul: Trans Soc Model Simul Int* 2012;89:381–91.

13. Romero G, Martinez ML, Felez J. Applicability of the GP device to the circle of Willis arteries by using a mathematical model. Presented at 13th International Conference on Computer Modelling and Simulation (UKSim), Cambridge, UK, March 30–April 1, 2011.
14. Burzotta F, Trani C, Romagnoli E, et al. Feasibility of sequential thrombus aspiration and filter distal protection in the management of very high thrombus burden lesions. *J Invasive Cardiol* 2007;19:317–23.
15. Giessen AG, Schaap M, Gijsen FJH, et al. 3D fusion of intravascular ultrasound and coronary computed tomography for in-vivo wall shear stress analysis: a feasibility study. *Int J Cardiovasc Imaging* 2010;26:781–96.
16. Cho YI, Kensey KR. Effects of the non-Newtonian viscosity of blood on flows in a diseased arterial vessel. Part 1: steady flows. *Biorheology* 1991;28:241–62.
17. Johnston BM, Johnston PR, Corney S, Kilpatrick D. Non-Newtonian blood flow in human right coronary arteries: steady state simulations. *J Biomech* 2004;37:709–20.
18. Soleimaniamiri S. Coronary clot removal by means of aspiration catheter: a numerical and experimental fluid dynamic study. PhD thesis, Politecnico di Milano, Milan, Italy, 2013.
19. Rosina J, Kvasnak E, Suta D, Kolarova H, Malek J, Krajci L. Temperature dependence of blood surface tension. *Physiol Res* 2007;56:93–8.
20. Vink MA, Kramer MC, Li X, et al. Clinical and angiographic predictors and prognostic value of failed thrombus aspiration in primary percutaneous coronary intervention. *JACC: Cardiovasc Interv* 2011;4:634–42.
21. Beygui F, Collet JP, Nagaswami C, Weisel JW, Montalescot G. Images in cardiovascular medicine. Architecture of intracoronary thrombi in ST-elevation acute myocardial infarction: time makes the difference. *Circulation* 2006 17;113:21–3.
22. Silvain J, Collet JP, Nagaswami C, et al. Composition of coronary thrombus in acute myocardial infarction. *J Am Coll Cardiol* 2011;57:1359–67.
23. Muller-Hulsbeck S, Bengard C, Schwarzenberg H, Gluer CC, Heller M. In vitro effectiveness study of three hydrodynamic thrombectomy devices. *Radiology* 1999;211:433–9.
24. Soleimani S, Pennati G, Dubini G. Numerical simulation of thrombus aspiration catheter: preliminary results. *IFMBE Proc Meditech* 2011;36:256–9.
25. Balossino R. A computational study of minimally-invasive devices for the treatment of coronary disease. PhD thesis, Politecnico di Milano, Milan, Italy, 2007.