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ORIGINAL ARTICLE

Reconstructive

Analysis of Major and Minor Pedicles in Flap Perfusion by Computational Fluid Dynamics

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Background: Type 2 muscle flaps are characterized by major and minor pedicles, such that the minor pedicle is unreliable, and the major pedicle is a requirement for the success of the flap. The role of the minor pedicle, beyond the decreased caliber and decreased vascular territory in comparison to the major pedicle, is poorly understood. We sought to model the fluid dynamics of a model flap containing a major and minor pedicle to understand differences between the pedicles and the implications on perfusion.

Methods: We first generated a computer-assisted design model of a type 2 flap with a major and minor pedicle. We then performed computational fluid dynamics to analyze velocities and flow within the pedicles and flap.

Results: In our investigation, we found that the flow velocity within the major pedicle was higher than the minor pedicle, indicative of decreased resistance to flow. Concomitantly, we found decreased pressures within the major pedicle, reflecting decreasing resistance to flow. Interestingly, we found increased kinematic viscosity in flap areas supplied by the minor pedicle, suggesting decreased flow rates and increased resistance.

Conclusions: We identified that the major pedicle has increased flow velocity, decreased resistance, and decreased kinematic viscosity, suggesting its dominance in maintaining flap perfusion. Our study also identifies computational fluid dynamics as a powerful tool in studying flap perfusion dynamics. *(Plast Reconstr Surg Glob Open 2024; 12:e5711; doi: 10.1097/GOX.0000000000005711; Published online 10 April 2024.)*

INTRODUCTION

Selecting the proper pedicle is an integral step in flap design. In general, vessels with larger diameters are favorable due to their decreased resistance to flow, increased capacity, and increased flow volume. This principle has been applied to the flap viability index, which relates the mass of tissue that can be harvested on the arterial diameter of the perforator, which can be obtained by computed tomography angiography or intraoperatively.[1] The perforasome theory revolutionized the understanding of the vascular territory of perforators and the role of direct and indirect linking vessels through computed tomography angiography of cadaveric flaps.[2] The study suggested that clinically significant perforators, through indirect and direct linking vessels which modulate multidirectional flow between perforators, have the potential to become a pedicle or a perforator flap.[2] Despite this, Mathes and Nahai had previously classified type 2 muscles as having major and minor pedicles, such that the minor pedicle is unreliable, and the major pedicle is a requirement for the success of the flap.[3] The role of the minor pedicle, beyond the decreased caliber and decreased vascular territory in comparison to the major pedicle, is poorly understood. We sought to model the fluid dynamics of a model flap containing a major and minor pedicle to understand differences between the pedicles and the implications on perfusion.

METHODS

A computer-assisted design (CAD) model of the flap was constructed in OnShape. The process involved three-dimensional construction of the flap and its vascular

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Table 1. Pedicle and Flap Dimensions

Pedicle Dimensions	
	Minor pedicle: 1-mm caliber
	Length: 70 mm
	Major pedicle: 2-mm caliber
	Length: 70 mm
Flap Dimensions	
	Flap length: 348.99 mm
	Flap width: 60 mm
	Flap height: 2.5 cm

Takeaways

Question: How do the differences in fluid dynamics between major and minor pedicles of flaps impact perfusion?

Findings: Through computational fluid dynamics, we identified that the major pedicle has increased flow velocity, decreased resistance, and decreased kinematic viscosity compared with the minor pedicle of the flap, suggesting its dominance in maintaining flap perfusion.

Meaning: The favorable flow characteristics of the major pedicle underscore its critical role in ensuring adequate perfusion and, hence, the viability of the flap.

pedicles. It was ensured that the entire structure was continuous with no mismatches or gaps, particularly in the vascular branches. The dimensions (Table 1) are consistent with previous reports of the gracilis flap, a type 2 flap.[4,5] The CAD model was then transferred to SimScale, where meshing and computational fluid dynamics (CFD) simulation was performed. Post processing within SimScale was performed to visualize data. Statistical comparison of velocities and pressures was performed by *t* test using GraphPad Prism.

RESULTS

Flap Design

We first generated a CAD model of a flap, with the following specifications (Table 1). The major pedicle had a 2-mm caliber, whereas the minor pedicle had a 1-mm caliber. The pressure at both the pedicles was set at 100 mm Hg, as previously reported,[6] which may overapproximate mean arterial pressure in the systemic circulation. The minor pedicle was given fewer branches and decreased area of flap perfusion, whereas the major pedicle was given more branches and increased area of flap perfusion (Fig. 1A and B). For simplicity, the indirect and direct linking vessels were excluded.

Flow and Kinematic Viscosity

In our investigation, we found that the flow velocity within the major pedicle was higher than the minor pedicle, indicative of decreased resistance to flow (Fig. 1C, 1D, and Fig. 2). In particular, there was significantly increased velocity within the major pedicle, compared with the minor pedicle, before branching ($P < 0.0001$; Fig. 3A). This corresponded to increased velocity fields in the flap vascular territory of the major pedicle, compared with the minor (Figs. 1C, D, and 3B). This outcome is consistent with the principles of fluid dynamics, wherein a larger

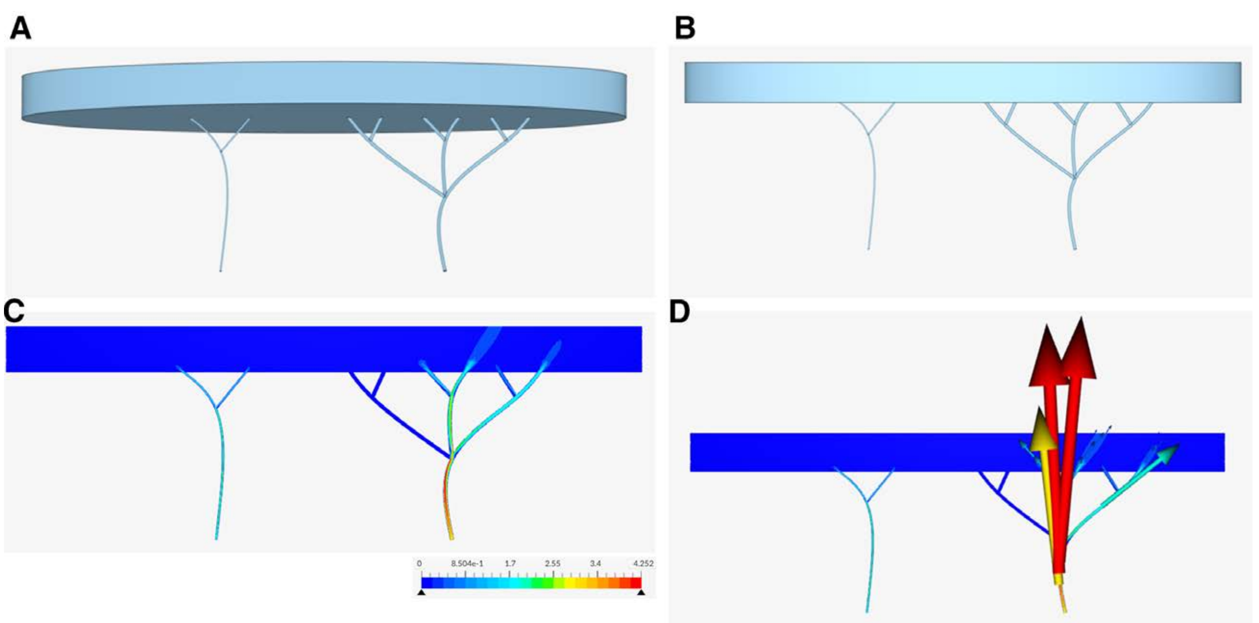

Fig. 1. CAD design of flap and velocity. Flap and pedicles were constructed according to dimensions in Table 1. A, The flap contains a major pedicle and a minor pedicle. B, A cross section of the flap and pedicles. C, Velocities within the pedicles, branches, and distal flap perfusion are shown (velocities shown in m/s according to color bar). D, Velocity vectors within the pedicles, branches, and distal flap perfusion are shown. Velocity is in m/s.

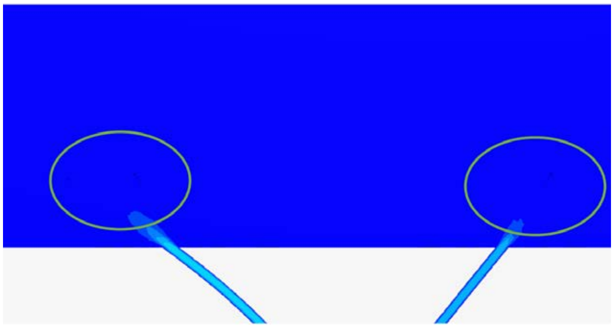

Fig. 2. Zoomed in area of perfusion for the minor pedicle, with circled velocity vectors, which are very small, indicating low velocity.

diameter correlates with decreased flow resistance. [**See Video (online),** which demonstrates increased flow velocity within the major pedicle, when compared with the minor pedicle.]

Our findings also revealed an increased kinematic viscosity within the flap territory nourished by the minor pedicle when contrasted with the major pedicle's domain (Fig. 4A). An increased kinematic viscosity suggests amplified resistance to flow and a concomitant reduction in flow rate, which could precipitate stasis and augment the potential for thrombus formation. Conversely, the area perfused by the major pedicle exhibited a reduced kinematic viscosity, aligning with lowered resistance to flow and enhanced perfusion efficacy. This is particularly important because vascular thrombosis remains a major cause of flap loss.[7]

Pressure

Concerning pressure dynamics, the minor pedicle exhibited increased pressures in comparison with the major pedicle. In particular, there was significantly increased pressure within the minor pedicle, compared with the major pedicle, before branching ($P < 0.05$; Figs. 3C and 4B). The major pedicle's reduced resistance to blood flow is consistent with the Poiseuille law, which posits that resistance is inversely proportional to the fourth power of the vessel's radius. Hence, a vessel of larger caliber facilitates easier blood flow, resulting in a proximal pressure decrement as blood is more efficiently distributed.

The distal pressures within the major pedicle were less than those within the minor pedicle. This is consistent with the Bernoulli principle, which states that an increase in fluid velocity leads to a reduction in its pressure. This principle extends along the vessel's length, resulting in a pressure reduction from the proximal to the distal ends. The minor pedicle, possessing a smaller radius and fewer branches, will exhibit a reduced flow velocity. Consequently, the pressure reduction from the proximal to distal ends is less accentuated than in the major pedicle. Despite regions of the distal circulation demonstrating negative pressures while maintaining positive velocities, we surmise these negative pressures to be simulation artifacts, given that the models do not account for physiologic vascular tone. The negative pressures are interpreted as a relative decrease in the distal branches when juxtaposed with the proximal vessel, representing diminished resistance to flow.

Within the flap itself, regions perfused by the major pedicle were found to have lower pressures relative to those serviced by the minor pedicle. This decreased flap pressure, mirroring interstitial pressure, is likely reflective of augmented blood flow to those territories, as evidenced by the velocity data.

DISCUSSION

Our study introduces the use of CAD and CFD to model flap perfusion dynamics. We demonstrate that CAD is a viable tool to construct models of flaps, which can be

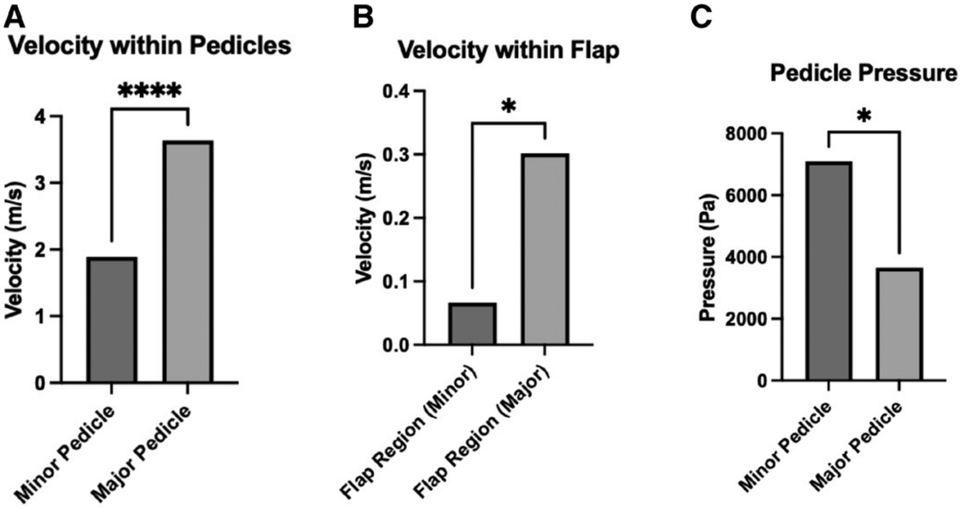

Fig. 3. Velocity and pressures with the pedicles and flap. A, Comparison of velocities within the major and minor pedicles by *t* test (seven areas per pedicle, pre-branch). B, Velocity within flap regions supplied by major and minor pedicles by *t* test (10 regions per pedicle). C, Comparison of pressures within the major and minor pedicles by *t* test (seven areas per pedicle, pre-branch). ****$P < 0.0001$, *$P < 0.05$.

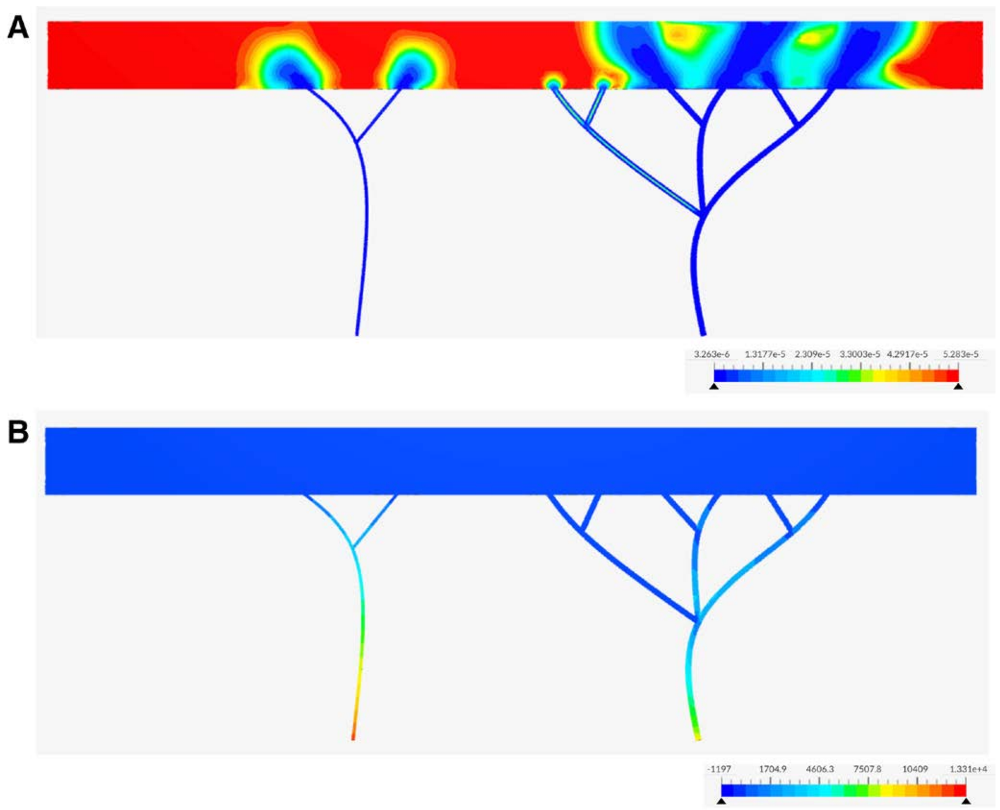

Fig. 4. Pressure and kinematic viscosity of pedicles and flap. A, Kinematic viscosity within the pedicles, branches, and distal flap perfusion are shown (kinematic viscosity shown in m^2/s according to color bar). B, Pressures within the pedicles, branches, and distal flap perfusion are shown (pressures shown in Pa according to color bar).

used to study fluid dynamics. Our analysis reveals favorable flow characteristics of the major pedicle compared with the minor pedicle. The larger diameter and reduced resistance not only facilitate higher flow rates but also minimize kinematic viscosity, which may lead to decreased vascular complications such as thrombosis. The increased pressures proximally and distally in the minor pedicle, while indicative of a viable vascular network, also suggest limitations in its capacity to sustain the flap independently. It is possible that the increased pressures within the minor pedicle likely result in increased back pressure and may impede vascular flow. The relatively low pressures within the major pedicle and its circulation suggests an efficient flow rate with minimal resistance to flow. This is particularly relevant in the context of flap harvesting, where the dominance of the major pedicle may allow for the strategic sacrifice of the minor pedicle without compromising the overall success of the flap transfer.

Our study is important in the context of developing next-generation precision flaps, whereby the surgeon is able to propose a flap on a patient, construct the model in CAD, perform CFD to comprehensively determine the perfusion pattern, and inform a more data-driven operative approach. Our CFD analysis provides intuitive visual schematics based on rigorous quantitative analysis, which are rapidly interpretable to determine dominant perfusing vessels.

Emerging data trends as more flaps are analyzed will also enable a predictive approach, whereby low-risk and high-risk perfusing vessels are readily identified and inform operative approach. Further studies are also necessary to more accurately understand the anatomic structure of flaps, particularly the distal circulation and the branching patterns to inform more accurate CAD design.

Our study had limitations, including the inability to control vascular tone in the vessel walls, and the exclusion of indirect and direct linking vessels. Nevertheless, the elimination of these variables allowed for a more streamlined and less convoluted analysis of the major determinants of flap perfusion: the pedicle architecture. CFD is a powerful and impactful method to analyze and predict flow. Recently, CFD was used to identify the impact of anastomotic angle on end-to-side anastomosis.[6] Our study demonstrates that CFD can be used to comprehensively analyze differential arrangement of pedicles and perforators or minor and major pedicles.

CONCLUSIONS

The implications of our study are multifold, providing insightful contributions to the role of major and minor pedicles in flap perfusion. The favorable flow characteristics of the major pedicle underscore its critical role in ensuring adequate perfusion and, hence, the viability of the flap. The larger diameter and reduced resistance result in higher flow rates and reduction in kinematic viscosity, which could potentially decrease vascular complications such as thrombosis.

Our findings in the minor and major pedicle provide a novel perspective on blood flow dynamics within vascular networks, and may have unique applications in the design of flaps, potentially informing surgical approaches to optimize blood flow and reduce the risk of postoperative complications.

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DISCLOSURE

The authors have no financial interest to declare in relation to the content of this article.

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