

Introduction

- Free flap hemodynamics remain incompletely characterized, as these constructs create non-physiologic flow conditions with a single inflow pedicle and loss of native vascular branching.
- Abrupt geometric transitions within the flap (e.g., pedicle-perforator junctions) generate wave reflections, producing complex flow patterns not captured by conventional intraoperative assessment. Current metrics, including Doppler flow and pulsatility index (PI), provide only gross estimates of flow and resistance, without assessing waveform quality or flow disturbance.
- Fourier-domain analysis enables decomposition of flow waveforms into harmonic components, allowing quantification of waveform complexity (harmonic distortion) as a surrogate of disturbed flow.
- A quantitative framework integrating flow, resistance (PI), and waveform distortion is needed to better characterize flap physiology and guide intraoperative assessment and optimization.

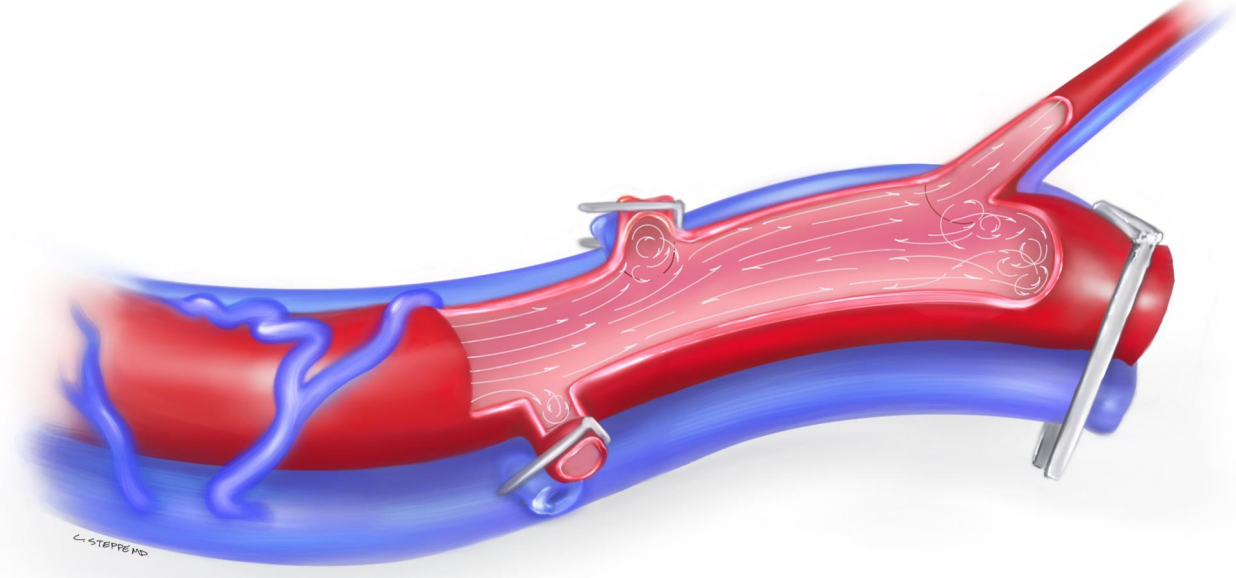


Figure 1 (above). A schematic representation of pulsatile flow in a perforator free flap. Anterograde flow waves (pedicle to perforator) encounter abrupt changes in vessel geometry (e.g., pedicle-perforator junction, clipped side branches, and the clipped distal end of the pedicle) that produce reflected waves.

Objective

To characterize the relationships among flow, pulsatility index, and harmonic distortion as complementary measures of free flap hemodynamics (Table 1).

Methods

- A retrospective review was conducted of patients who underwent microvascular free tissue transfer at a single academic institution from 3/2024 to 11/2025. Anterolateral thigh (ALT), deep inferior epigastric perforator (DIEP), and latissimus dorsi (LD) flaps were included.
- Intraoperative flow measurements were obtained at the arterial anastomosis using a transit-time flowmeter after completion of both the arterial and venous anastomoses but before flap inset.
- Recorded parameters included time-resolved flow, pulsatility index (PI), and acoustic coupling index (ACI). Mean flow and PI were recorded when the signal demonstrated stable morphology and the ACI exceeded 50%.
- Arterial and venous pedicle calibers were recorded intraoperatively using a caliber gauge, with vessel caliber defined as the average internal diameter of the two anastomosed vessels.
- Flow waveforms were sampled at 201 Hz for a minimum of 15 seconds per recording, and a short-time Fourier transform was applied using 4-second windows with 1-second step intervals to characterize waveform harmonic content.
- Harmonic distortion (HD) was calculated as the ratio of cumulative harmonic power to fundamental frequency power and quantified as HD1, HD5, and HD10.
- Between-flap differences and continuous relationships were evaluated using Kruskal-Wallis testing, post hoc Mann-Whitney comparisons, Pearson correlation, and multivariable linear regression.

Results

Table 1. Mapping of hemodynamic concepts to measured intraoperative metrics. This table highlights three clinically relevant domains but is not intended to be exhaustive. <i>"While true turbulence is unlikely at the microvascular scale, the term "turbulence" is used conceptually to describe disturbed flow.</i>				
Concept	Definition	Measured analog	Description	Relevance
Flow	Volume of blood delivered	Flow (mL/min)	Mean volumetric blood flow through the arterial pedicle	Higher values indicate improved perfusion of flap tissue
Resistance	Steady opposition to flow	Pulsatility index (PI, unitless)	Relative variation in flow (i.e., pulsatility) over the cardiac cycle	Higher values suggest less favorable downstream flow conditions
Turbulence*	Flow disturbance and waveform irregularity	Harmonic distortion (HD, unitless)	Distribution of energy across harmonic frequencies	Higher values suggest more disturbed or irregular flow patterns

Cohort Characteristics

- Data from 70 free flaps performed in 51 patients between March 2024 and November 2025 were reviewed. Flap types included 47 DIEP flaps (67.1%), 14 ALT flaps (20.0%), and 9 LD flaps (12.9%).
- Mean arterial inflow was 9.0 mL/min (SD=5.85) and mean PI was 3.8 (SD=3.76). Arterial pedicle caliber was 1.76 mm (SD=0.29) and venous pedicle caliber was 2.35 mm (SD=0.52).

Flow and PI by Flap Type (Table 2)

- Average flow was 5.50 mL/min (SD=3.35) in ALT flaps, 9.15 mL/min (SD=5.07) in DIEP flaps, and 13.33 mL/min (SD=9.29) in LD flaps.
- When stratified by flap type, median flow differed significantly ($P=0.006$), with ALT versus DIEP ($P=0.03$) and ALT versus LD ($P=0.02$) differing significantly on post hoc testing.
- Average PI ranged from 5.76 (SD=4.38) in ALT flaps, 3.57 (SD=3.68) in DIEP flaps, and 2.23 (SD=1.77) in LD flaps.
- Median PI also varied by flap type ($P=0.006$); ALT versus DIEP ($P=0.03$) and ALT versus LD ($P=0.03$) again differed significantly on post hoc testing.

Pedicle Caliber by Flap Type

- Pedicle caliber varied by flap type, with DIEP flaps demonstrating the largest arterial pedicles, while ALT and LD flaps were similar.
- Median arterial caliber differed significantly ($P=0.04$), though post hoc tests did not reach significance. ALT flaps had the smallest venous pedicles.
- Median venous calibers differed significantly ($P=0.02$), with ALT versus DIEP reaching significance on post hoc testing ($P=0.01$).

Spectral Power and Harmonic Distortion (Figure 2)

- Spectral power was concentrated within the fundamental and lower-order harmonics, with little power beyond the 10th harmonic.
- Mean HD values were 0.36, 0.52, and 0.55 for HD1, HD5, and HD10, respectively.

Harmonic Distortion by Flap Type

- ALT flaps demonstrated the greatest harmonic distortion, whereas DIEP flaps had the lowest low-order distortion.
- HD1 and HD5 differed significantly by flap type, driven by ALT-DIEP differences (HD1 $P=0.002$; HD5 $P=0.03$).
- At HD10, DIEP and LD converged, while ALT remained higher ($P=0.06$).

Associations with Arterial and Venous Caliber

- Arterial caliber was not associated with flow, PI, or HD.
- Larger venous caliber correlated with higher flow, lower PI, and lower HD across harmonic orders.

Relationships Among Hemodynamic Metrics (Figure 3-4)

- Across the cohort, PI was strongly inversely related to flow ($r=-0.71$, $P<0.001$) (Figure 3) and positively associated with harmonic distortion (HD1: $r=0.43$, $P<0.001$; HD5: $r=0.49$, $P<0.001$; HD10: $r=0.51$, $P<0.001$).
- Notably, HD-vein associations were strongest at low orders (HD1), whereas HD-PI associations strengthened when including higher-order content (HD10) and were larger in magnitude overall.
- After adjusting for flap type, flow and PI exhibited an approximately inverse square-root relationship ($\beta=-0.54$, 95% CI: -0.69, -0.39], $P<0.001$).

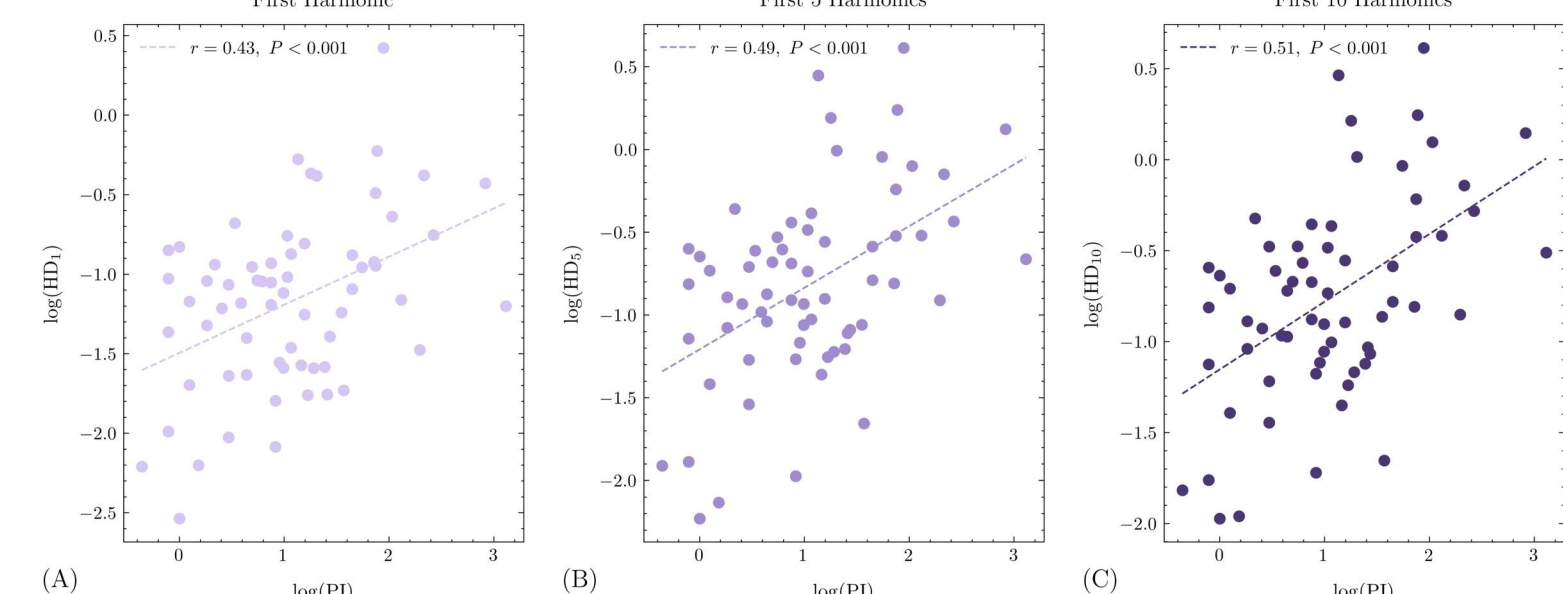


Figure 3. Comparison of harmonic distortion ratios computed as the cumulative power of the first harmonic only (A), the first five harmonics (B), and the first ten harmonics (C) as a function of the pulsatility index (PI). Lower harmonic distortion corresponds to more uniform flow. The plot indicates that as PI increases, flow becomes less uniform

Table 2. Vessel caliber, flow, pulsatility index (PI), and harmonic ratios across deep inferior epigastric perforator (DIEP), anterolateral thigh (ALT), and latissimus dorsi (LD) flaps. HD ₁ , HD ₅ , and HD ₁₀ denote the cumulative harmonic distortion calculated using the first 1, 5, and 10 harmonics, respectively. Reported P-values indicate overall group differences across the three flap types using Kruskal-Wallis tests.			
	DIEP	ALT	LD
Arterial Caliber, mm ($P=0.04$)			
Mean (SD)	1.83 (0.24)	1.60 (0.32)	1.60 (0.37)
Median [IQR]	1.8 [1.7 – 2.0]	1.6 [1.4 – 1.9]	1.6 [1.5 – 1.9]
Venous Caliber, mm ($P=0.02$)			
Mean (SD)	2.45 (0.44)	1.95 (0.50)	2.44 (0.73)
Median [IQR]	2.5 [2.2 – 2.8]	1.8 [1.5 – 2.3]	2.1 [2.0 – 3.0]
Flow, mL/min ($P=0.006$)			
Mean (SD)	9.15 (5.07)	5.50 (3.35)	13.33 (9.29)
Median [IQR]	9.0 [5.0 – 12.5]	5.0 [3.0 – 6.8]	12.0 [7.0 – 15.0]
PI ($P=0.006$)			
Mean (SD)	3.57 (3.68)	5.76 (4.38)	2.23 (1.77)
Median [IQR]	2.6 [1.6 – 3.8]	5.0 [3.2 – 6.8]	1.7 [1.0 – 2.4]
HD ₁ ($P=0.002$)			
Mean (SD)	0.29 (0.13)	0.56 (0.36)	0.38 (0.08)
Median [IQR]	0.28 [0.19 – 0.35]	0.43 [0.34 – 0.69]	0.39 [0.31 – 0.44]
HD ₅ ($P=0.03$)			
Mean (SD)	0.44 (0.24)	0.81 (0.52)	0.47 (0.08)
Median [IQR]	0.38 [0.30 – 0.59]	0.56 [0.45 – 1.13]	0.48 [0.44 – 0.52]
HD ₁₀ ($P=0.06$)			
Mean (SD)	0.48 (0.25)	0.82 (0.52)	0.48 (0.08)
Median [IQR]	0.40 [0.31 – 0.62]	0.56 [0.46 – 1.16]	0.49 [0.44 – 0.53]

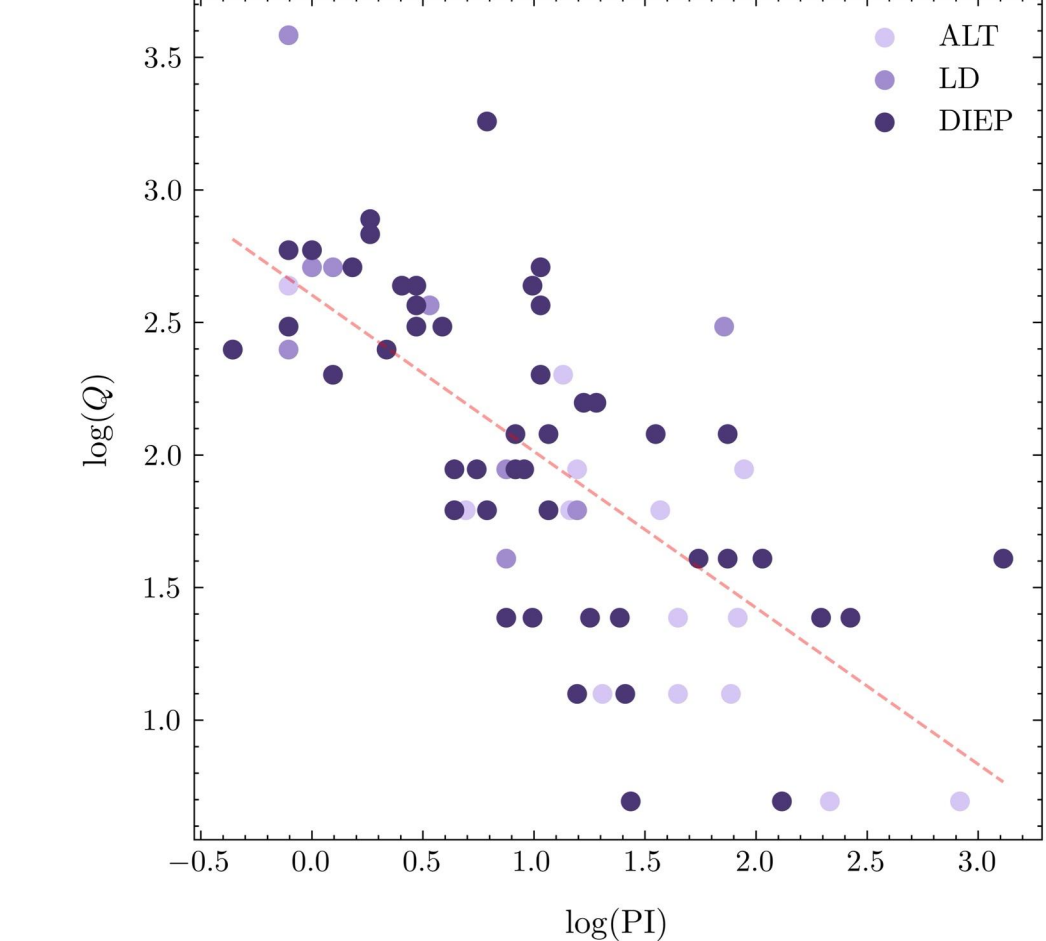
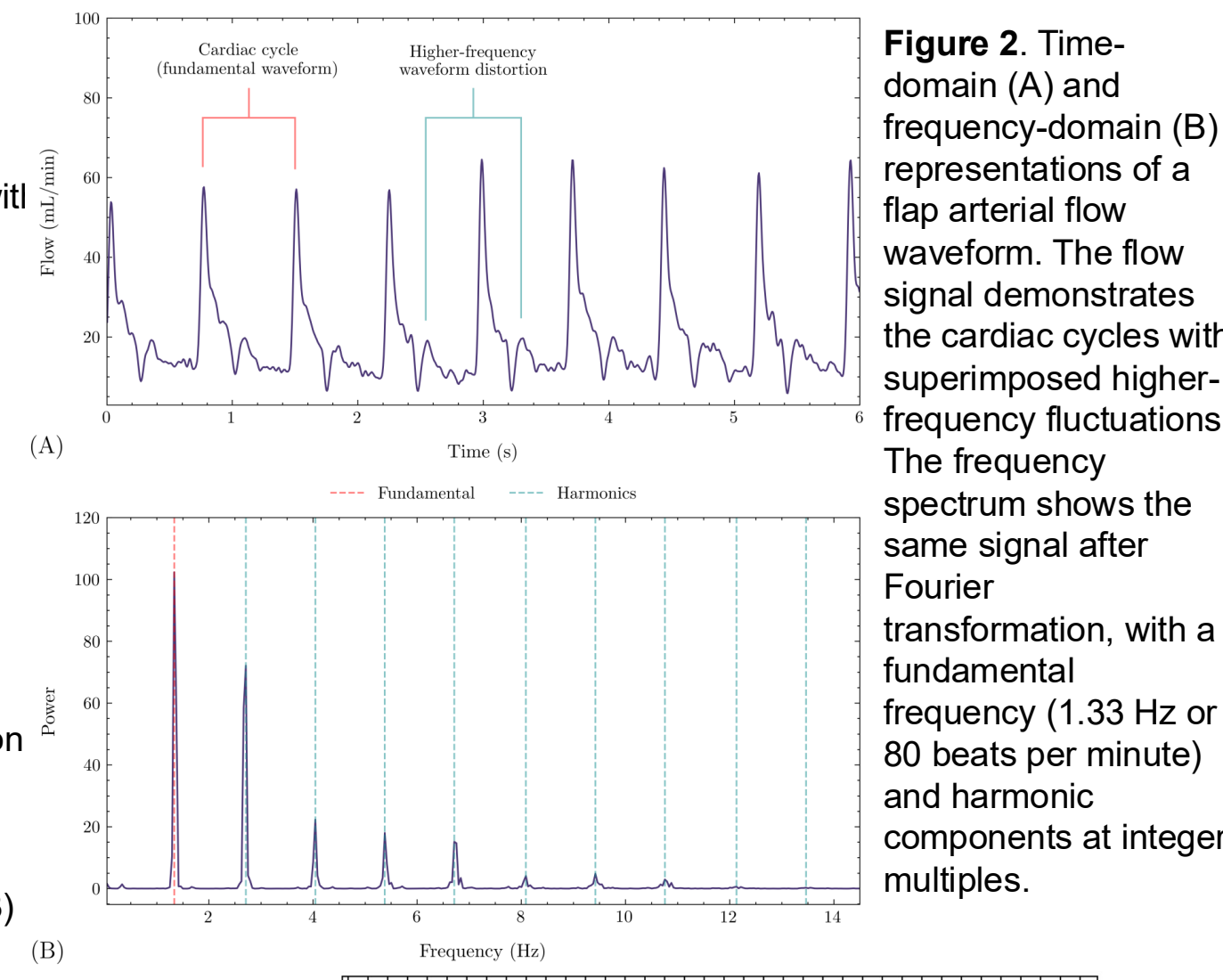


Figure 4. Flow (Q) versus pulsatility index (PI) in free flaps. The plot shows that as PI decreases, flow increases. ALT = anterolateral thigh; LD = latissimus dorsi; DIEP = deep inferior epigastric perforator

Discussion

Flow-Resistance Relationship

- Flow and PI were strongly and inversely related, supporting PI as a surrogate of downstream resistance and flow limitation.
- The relationship was nonlinear, with flow increasing approximately with the inverse square root of PI, indicating PI reflects effective rather than absolute resistance.
- Changes in PI do not translate proportionally to flow, highlighting the influence of vascular compliance and flap architecture beyond simple resistance models.

Harmonic Distortion as a Novel Metric

- Harmonic distortion (HD) captures waveform complexity and flow quality, providing information not reflected by flow or PI alone.
- HD increased with higher PI, linking unfavorable hemodynamic states to greater waveform distortion.
- Discordance between flow and HD (e.g., high flow with persistent distortion) suggests normal flow may coexist with abnormal hemodynamics.

Wave Reflection and Flap Physiology

- Wave reflections from abrupt geometric transitions contribute to disturbed flow and increased waveform complexity.
- Increased harmonic content may reflect inefficient forward flow and adverse hemodynamic conditions, with potential relevance to thrombosis risk.
- Fourier-based analysis enables functional characterization of flap perfusion beyond anatomic descriptors.

Flap Architecture and Hemodynamic Signatures

- Distinct flap types demonstrated characteristic hemodynamic profiles, suggesting architecture directly influences flow behavior.
- Even similarly classified flaps (e.g., ALT vs DIEP) exhibited meaningful physiologic differences, indicating flaps are not hemodynamically interchangeable.
- Harmonic distortion may serve as a "fingerprint" of flap physiology, with deviations signaling abnormal flow states.

Dominant Role of Venous Outflow

- Venous caliber, not arterial caliber, was strongly associated with higher flow, lower PI, and reduced waveform distortion.
- These findings support that free flaps are outflow-limited systems, with venous drainage as the dominant determinant of hemodynamics.
- Optimizing venous outflow (e.g., larger veins or dual venous anastomoses) may therefore be more critical than augmenting arterial inflow.

Clinical Implications and Future Directions

- PI and HD provide complementary intraoperative metrics for assessing flap perfusion and identifying suboptimal flow states.
- Spectral analysis may enable early detection of evolving pathology (e.g., venous congestion, thrombosis).
- Future studies should evaluate whether these metrics predict clinical outcomes and guide intraoperative decision-making.

Conclusion

Free flap perfusion reflects a dynamic equilibrium among flow, resistance, and turbulence. Pulsatility index and harmonic distortion provide quantitative surrogates for resistance and waveform complexity, respectively.

References

- Kassab GS. Scaling laws of vascular trees: Of form and function. *Am J Physiol Heart Circ Physiol*. 2006;290(2):H884-903. doi:10.1152/ajpheart.00579.2005
- Kozmenko I, Sorensen S. Inferior epigastric artery skin flaps without rectus abdominis muscle. *Br J Plast Surg*. 1985;42(6):645-646. doi:10.1054/bjps.1985.00075.1
- Maffee SJ, Vaynsky L. Myocutaneous free-flap transfer. Anatomical and experimental considerations. *Plast Reconstr Surg*. 1978;62(2):162-166. doi:10.1097/00006534-197806000-00002
- Walton ZJ, Craig RD, Orion CI. The free latissimus dorsi myocutaneous flap. *Plast Reconstr Surg*. 1979;64(3):399-305. doi:10.1097/00006534-197903000-00002
- Coscia V, Rubino C. Hemodynamic enhancement in reconstructive surgery: Mathematical model and clinical findings. *Math Comput Model*. 2005;42(10):1151-1161. doi:10.1016/j.mcm.2004.11.005
- Rubino C, Coscia V, Cavazzuti AM, Caru V. Hemodynamic enhancement in perforator flaps: The inversion phenomenon and its clinical significance. A study of the relation of blood velocity and flow between pedicle and perforator vessels in perforator flaps. *J Plast Reconstr Aesthet Surg*. 2006;26(9):636-643. doi:10.1016/j.jps.2005.07.010
- Vlachopoulos C, O'Rourke M, Nichols WW, McDonald's Blood Flow in Arteries: Theoretical, Experimental and Clinical Principles, 6th ed. CRC Press; 2011. doi:10.1201/b11566
- Mynard JP, Kozlovskaya A. Wave reflection in the arterial tree. In: *Textbook of Arterial Stiffness and Pulsatile Hemodynamics in Health and Disease*. Elsevier; 2022:169-194. doi:10.1016/B978-0-323-93911-3.00011-3
- Tucker T. Physics linkages between arterial morphology, pulse wave reflection and peripheral flow. *Artery Res*. 2023;29(2):46-71. doi:10.1007/s44200-023-00033-5
- Mansory C, Angeli T, Tapp RL, et al. Wave reflection predicts cardiovascular events in hypertensive individuals independent of blood pressure and other cardiovascular risk factors: an ASCOT (Anglo-Scandinavian Cardiac Outcome Trial) substudy. *J Am Coll Cardiol*. 2010;56(1):24-30. doi:10.1016/j.jacc.2010.03.030