

Quantifying Blood Flow in the DIEP Flap: An Ultrasonographic Study

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Background: The maximum weight of tissue that a single perforator can perfuse remains an important question in reconstructive microsurgery. An empirically based equation, known as the flap viability index (FVI), has been established to determine what weight of tissue will survive on one or more perforators. The equation is $FVI = \sum d(n)^4 / W$, where d is the internal diameter of each perforator and W is the final weight of the flap. It has been shown that if FVI exceeds 10, total flap survival is likely, but if under 10, partial flap necrosis is probable. The aim of this study was to measure absolute flow rates in deep inferior epigastric perforator (DIEP) flap pedicles and assess correlation with the determinants of the FVI, perforator diameter and flap weight.

Methods: Color Doppler ultrasound was used to quantify arterial flow in 10 consecutive DIEP flap pedicles 24 hours after anastomosis.

Results: In single-perforator DIEP flaps, flow rate was highly correlated with perforator diameter ($r = 0.82$, $P = 0.01$). Mean arterial flow rate was significantly reduced in DIEP flaps with 2 or more perforators (6 vs 38 cm^3/min ; $P < 0.05$).

Conclusions: This study confirms that perforator size is a critical factor in optimizing blood flow in perforator-based free tissue transfer. Further research is required to understand the flow dynamics of perforator flaps based on multiple perforators. However, surgeons should be cognizant that a single large perforator may have substantially higher flow rates than multiple small perforators. Routine FVI calculation is recommended to ensure complete flap survival. (*Plast Reconstr Surg Glob Open* 2014;2:e228; doi: 10.1097/GOX.0000000000000191; Published online 3 October 2014.)

It can be difficult to obtain accurate measurements of in vivo blood flow in human fat and skin tissue as a result of measurement errors and the physiological milieu surrounding the vessels.¹⁻³ Even when mea-

surement error can be minimized, other factors such as vascular shunting, vascular anastomotic channeling, metabolic changes, and the presence of vasoactive mediators may alter flow readings. The perforator-based free flap offers a “human laboratory” that isolates a known weight of this tissue on a single vascular pedicle in a reproducible physiological environment. Using this model, the blood flow required for survival of a known mass of tissue can be accurately measured.

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The deep inferior epigastric perforator (DIEP) flap is a reliable, large volume free flap, routinely used in reconstructive microsurgery and, in particular, breast reconstruction. Maximizing the amount of viable tissue in the flap for breast reconstruction is of paramount importance for surgical success and patient satisfaction. Partial flap loss results in suboptimal outcomes and a higher risk of other surgical complications such as infection and revisional surgery for debridement of necrotic tissue. Strategies for minimizing partial or complete flap necrosis have been previously reported.⁴⁻¹⁴

The maximal weight of flap that will survive on a certain perforator diameter can be predicted using an empirical formula derived from Poiseuille's law, known as the flap viability index (FVI).¹⁵ **See Supplemental Digital Content 1**, which displays relevant equations: Poiseuille's law, FVI equation, FVI predicted flap weight calculation, and FVI single-perforator sustainability chart, <http://links.lww.com/PRSGO/A52>. The formula relies on preoperative computed tomography (CT) angiography to map and measure the number, size, and position of the perforators of the deep inferior epigastric artery. The equation is $FVI = \sum d(n)^4 / W$, where d is the internal diameter of each used perforator in millimeters and W is the final weight of the flap in kilograms. It has been shown that if FVI exceeds 10, total flap survival is likely, but if under 10, partial flap necrosis is probable. Since publication of the series documenting the FVI, the senior author has performed a further 55 breast reconstruction with DIEP flaps in which routine preoperative CT angiography and FVI calculation were performed. There was only one case of marginal skin and fat necrosis in a flap with an FVI of 7.6, which is below the safe level of 10 reported in the original article. This confirms the validity of the original proposition that flaps with an FVI less than 10 are at risk of marginal necrosis. To date, correlation of absolute blood flow with the predictions of the FVI has not been studied.

Color Doppler remains the standard method for quantifying blood flow with ultrasound.³ Based on the principle of uniform insonation, volumetric blood flow quantification entails using the Doppler principle to measure the time-averaged mean velocity of blood flowing through a vessel and multiplying it by the cross-sectional area of the lumen.

We aimed to use color Doppler ultrasonography to quantify postoperative blood flow in DIEP flap pedicles and to correlate these measurements with both perforator diameter and flap weight. Measuring absolute flow rates through DIEP pedicles and correlating these findings with the FVI allowed us to study its utility in predicting flap survival.

PATIENTS AND METHODS

Patients

Ten consecutive patients undergoing delayed breast reconstruction with a DIEP free flap between July 1, 2013, and February 1, 2014, were prospectively enrolled.

Procedure

All patients underwent routine preoperative CT angiographic mapping and measurement of abdominal perforator internal diameter, at the point of exit from the rectus sheath, followed by the same DIEP-based breast reconstruction procedure by the senior surgeon (D.G.P.). Highly detailed description of the perforator mapping technique, FVI calculation, and flap harvesting procedure has been published previously.¹⁵ The flap was weighed accurately once harvested, and a final flap weight recorded after all surplus tissue had been trimmed. At the conclusion of the case, the course of the flap pedicle was drawn on the skin paddle of the flap from the thoracodorsal anastomosis to the point of perforator entry into the flap. The midpoint of this line was marked as the position for ultrasound measurement.

Twenty-four-hour postoperative arterial flow rate was measured at the patient's bedside using an advanced ultrasonographic system and independent specialist ultrasonographer data collection (iU22 xMATRIX ultrasound system with Linear 12-5 MHz transducer; Phillips Electronics, Andover, MA). A series of five flow measurements were recorded to ensure consistency. Representative images were then produced for each patient before the final analysis (Fig. 1). In cases where the diameter of the pedicle was less than the minimum aperture of the calipers for volumetric flow analysis (0.197 cm), the vessel diameter was measured independently (Fig. 2). Volumetric flow was then recalculated manually to account for the smaller cross-sectional area.

Patients were followed-up by the senior surgeon regularly during the flap healing phase and at up to 12 months postoperatively (mean, 8.4 months). No flap in this small pilot series suffered any type of necrosis during that period.

Ethics approval was granted by the Research Ethics Committee of Macquarie University Hospital, Sydney Australia.

Statistical Analysis

Experimental data were analyzed using both Microsoft Excel (Microsoft Corporation, Redmond, Wash.) and the statistical software package SPSS (SPSS, Chicago, Ill.). Statistical analysis of correlation was performed using the Pearson correlation coefficient with 2-tailed P -values less than 0.05 considered significant.

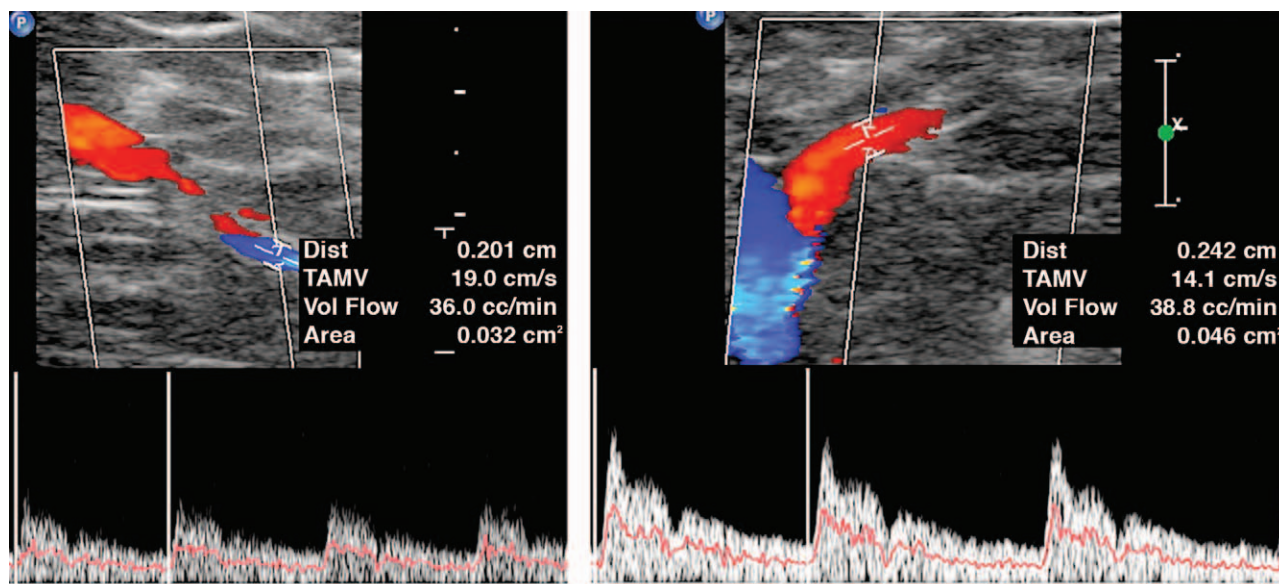


Fig. 1. Representative ultrasonographic images demonstrating the use of color Doppler to measure volumetric flow. TAMV indicates total area mean volume.

RESULTS

Data on perforator number and diameter, flap weight, FVI calculations, measured DIEP pedicle diameter, and blood flow rates are shown in Table 1. The perforator diameter/flow rate scatter plot of single-perforator DIEP flaps is shown in Figure 3.

One of the 10 prospectively enrolled patients was subsequently excluded from the study as the flap harvested included a small portion of rectus abdominis muscle, defining this as a transverse rectus abdominis myocutaneous flap instead of a DIEP flap. Of the remaining 9 patients, 7 were single-perforator DIEP flaps and 2 used more than 1 perforator. The average

perforator diameter measured using CT angiography preoperatively was 1.55 mm (0.9–1.8). The average flap weight was 637 g (381–970), and the average FVI was 14.2 (8.7–25.7). Preoperative internal perforator diameter correlated well with postoperatively measured pedicle diameter, indicating that the flap pedicle was measured at a consistent distance from the anastomosis in each case ($r = 0.84$, $P = 0.01$).

Mean volumetric flow in single-perforator DIEP flaps was 38 cm³/min (12.5–73), and the mean rate of volumetric blood flow by weight in single-perforator flaps was 6.5 cm³/min/100 g (3.2–15.5). Volumetric flow measurements were highly correlated with the perforator diameter ($r = 0.82$, $P = 0.01$), and although there was a positive correlation between volumetric flow and the flap weight, this was not statistically significant ($r = 0.53$, $P = 0.1$). Mean flow in DIEP flaps with 2 or more perforators was significantly reduced (6 vs 38 cm³/min; $P < 0.05$).

DISCUSSION

The laws of fluid dynamics demonstrate that, for a noncompressible fluid such as blood, measurement of flow at any point along a source vessel, so long as it is proximal to any branching point, represents the total flow in the system. They also establish that the flow rate through any system is limited by the part of the system that has the narrowest diameter, the so-called choke area.^{16,17} For the perforator flap vascular system, this choke area is at a point where each perforator is narrowest, just before it enters the flap and arborizes. After arborizing, the resistance of the system becomes the capillary bed.¹⁷ This choke zone after dissection of

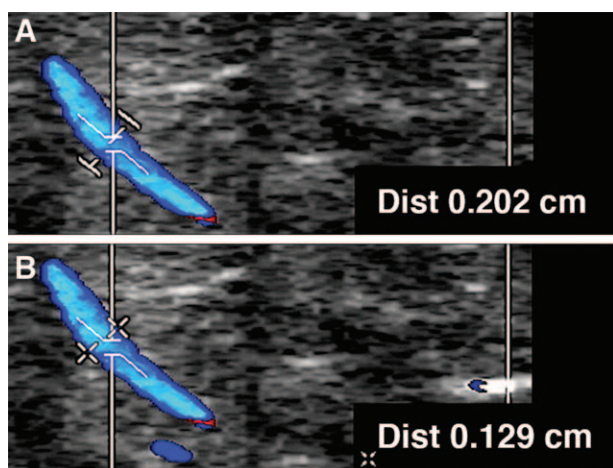


Fig. 2. A, Example of difficulty calculating volumetric flow when pedicle diameter was less than the minimum aperture available using the flow measurement calipers. B, Accurate measurement of the pedicle diameter to enable manual recalculation of the volumetric flow.

Table 1. Pre- and Postoperative Measurements and Calculations

Patient No.	No. Perforators	Perforator Diameter (PerfDiam) (mm)	Sum (PerfDiam ⁴)	Net Flap Weight (kg)	FVI	Measured DIEP Pedicle Diameter (cm)	Volumetric Flow (cm ³ /min)	Average Blood Flow Rate (cm ³ /min/100g)
1	1	1.6	6.6	0.755	8.68	0.168	24.3	3.2
2	1	1.4	3.8	0.261	14.72	0.103	12.5	4.8
3	1	1.5	5.1	0.381	13.29	0.197	14.4	3.8
4	1	1.7	8.4	0.414	20.17	0.179	64.2	15.5
5	1	1.6	6.6	0.68	9.64	0.201	36.0	5.3
6*	2	1.5, 1.4	8.9	0.732	12.16	0.129	4.0	0.6
7	MS-TRAM							
8*	3	1.8, 1.6, 0.9	17.7	0.69	25.67	0.136	7.9	1.1
9	1	1.8	10.5	0.97	10.82	0.299	72.9	7.5
10	1	1.8	10.5	0.851	12.34	0.242	38.8	4.6

*Case based on 2 or more perforators.

MS-TRAM, muscle-sparing transverse rectus abdominis myocutaneous flap harvest.

the DIEP flap pedicle is located where the perforator exits from the rectus sheath to enter the flap.¹⁵

We have previously shown that the viability of the free DIEP flap can be predicted preoperatively by using CT angiography to measure the diameter of all abdominal perforators and applying the FVI.¹⁵ Recent advancements in ultrasonographic technology have enabled the detection and analysis of blood flow in very small vessels at a depth of up to 100mm. Color Doppler flowmetry has also enabled measurement of volumetric blood flow in many areas of clinical medicine, including coronary bypass procedures, renal arteries, carotid arteries, and in peripheral vascular disease.¹⁸ Ultrasonic probes have been in use for diagnosis and monitoring after free flap surgery for many years and are widely recognized as safe and minimally invasive techniques that avoid the use of ionizing radiation.^{19,20} A number of articles have addressed their use in DIEP flaps for various purposes.^{1,2,11,20-25} However,

few studies have specifically looked at quantifying the volumetric blood flow through free flap pedicles.

Lorenzetti et al²⁴⁻²⁶ showed that the flap blood supply in transverse rectus abdominis myocutaneous flaps is independent of the preoperative flow in the recipient vessel and that flow is related to flap weight. Rubino et al¹¹ measured the arterial flow rates in free DIEP pedicles and used this information to infer principles about venous sufficiency of DIEP flaps. Their absolute findings correlate very well with our study for mean arterial volumetric flow (37.8 vs 38.0cm³/min) and mean rate of volumetric blood flow by weight (6.3 vs 6.5cm³/min/100g). The mean DIEP flap weight, however, was less than our series (580 vs 637g) despite larger mean perforators (2.3 vs 1.6mm). They also found a stronger correlation between flap weight and volumetric flow rates ($r = 0.73$ vs 0.53) and a lower correlation between flow and perforator diameter than in the cur-

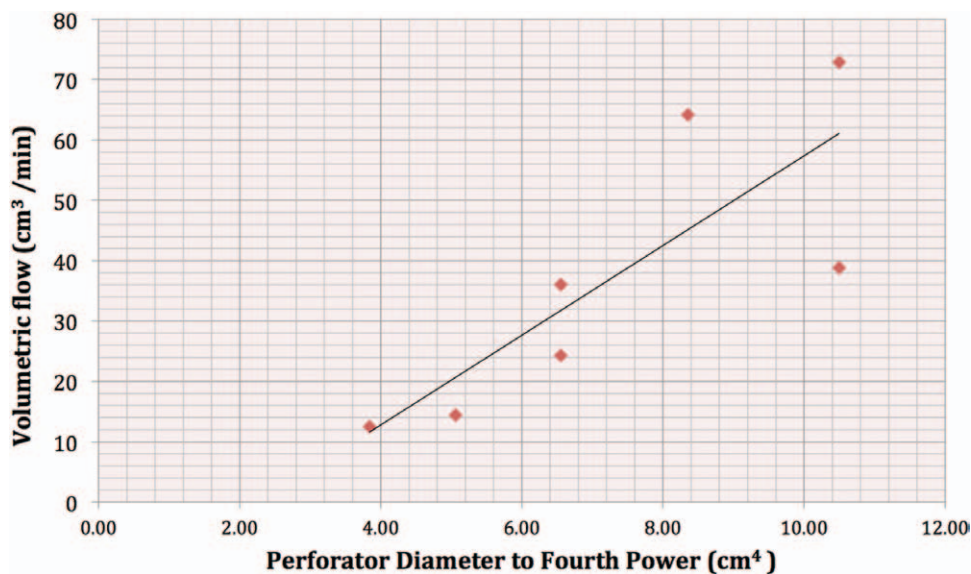


Fig. 3. Scatter plot showing the positive linear correlation between perforator diameter and volumetric flow in single-perforator DIEP flaps ($r = 0.82, P = 0.01$).

rent study ($r = 0.67$ vs 0.82). The differences in their findings may relate to differences in both method of measurement and timing of sonographic assessment (1 month after surgery to measure the flap hemodynamics at equilibrium). This time delay may have allowed peripheral neovascularization and therefore confounded their data. We decided that postoperative day 1 was likely to represent not only a critical time for flap viability but also the most pure example of isolated flow through the flap pedicle.

Despite these differences, the findings of these 2 studies are largely complementary and reinforce the significance and utility of the FVI. Rubino et al¹¹ inferred from their data that larger flaps will have a higher flow rate. Although this may be true up to a certain level of flow, it is logical that there will be a maximum amount of flow that any particular vessel can deliver, and this amount will ultimately be dependent on the diameter of the vessel. After this point, any further increases in flap weight will likely lead to arterial insufficiency and ischemic partial flap necrosis. Determining this critical level of blood flow is the clinical question that the FVI seeks to address. We consider flow above this level to be a safe level of blood flow. By taking into consideration both the perforator diameter and the flap weight, the FVI enables safe estimation of maximal flap weight for any given perforator diameter. (See **Supplemental Digital Content 1**, which displays relevant equations: Poiseuille's law, FVI equation, FVI predicted flap weight calculation, and FVI single-perforator sustainability chart, <http://links.lww.com/PRSGO/A52>.)

Limitations of Color Doppler ultrasound measurements are that they can be operator dependent and prone to recognized errors.^{1,2} A recent phantom-controlled physiological study testing blood flow measurement using various ultrasound systems (including the system used in this study) showed that reasonable accuracy can be expected provided users are adequately trained, experienced, perform multiple measurements, and use known techniques to minimize controllable errors.³ Despite following these guidelines, we encountered difficulties in our study specific to the measurement of blood flow in free flap pedicles. First, the smallest possible aperture of the vessel defining calipers in our operating system was 0.197 cm (Fig. 2). If the actual vessel diameters were smaller and these were to go uncorrected, this would lead to a gross overestimation of flow. In fact, this problem was easily remedied by measuring the vessel diameter separately and by recalculating cross-sectional vessel area manually, yielding volumetric flow. (See **Supplemental Digital Content 1**, which displays relevant equations: Poiseuille's law, FVI equation, FVI predicted flap weight calculation,

and FVI single-perforator sustainability chart, <http://links.lww.com/PRSGO/A52>.)

The second difficulty we faced was when multiple perforators had been harvested. It was difficult to determine which portion of the flap pedicle was being scanned and, if distal to a branching point, then which perforating vessel was being analyzed. We found flow measurements to be significantly lower in these cases (6 vs 38 cm³/min; $P < 0.05$). This may be because our measurements were taken distal to a branching point or because the actual flow rate in a flap pedicle with 2 or 3 branches is lower. Although this latter conclusion may seem counterintuitive, the literature published on the clinical efficacy of DIEP flaps based on multiple perforators is varied.^{17,27–30} The current recommendation from high-volume DIEP flap reconstruction teams is to use the single largest perforator, which agrees with the findings of this study.^{29,31,32} A theoretical study by Patel and Keller¹⁷ likens the flow in a free flap based on multiple perforators to an electrical circuit in parallel. The resistance of the larger diameter vessel will be much lower (to the 4th power) than the resistance of any additional smaller perforator, and so the effect of the smaller vessel in terms of increasing total flow may be minimal or even negligible. Unfortunately, no study has isolated flaps of equal weight on differing number of perforators and assessed flap viability. Flaps that have been harvested using multiple perforators are usually large and/or are supplied by small or peripherally located perforators, and so conclusions based on the clinical outcomes of such flaps should be interpreted with caution.⁹ Our finding of reduced flow in such cases may be due to the choke areas in each of these small perforators in fact leading to a reduction in absolute flow compared to similar sized flaps based on a single large perforator. Further study will be required to delineate the hemodynamics of perforator flaps based on several perforating vessels. As a result of this significant disparity of flow rates, we did not include flaps based on multiple perforators in our final analysis.

We are aware that there exists in the literature a contention that “venous insufficiency” may be a cause of partial flap necrosis and that this can be a particular concern in the DIEP flap.^{7,19,21,30,33} Diagnosis of “venous insufficiency” has been made clinically, upon the observation of sluggish capillary refill, dusky or blue hue of the skin, and patent anastomoses. A laser Doppler flowmetry and lightguide reflectance spectrophotometry study of microcirculation showing evidence of static flow and deoxygenation has been used to give credence to the theory of “venous insufficiency.”³³ This has led to supplementation of superficial venous anastomosis to the deep venous anastomosis in certain cases.^{9,21} If, as some of the authors suggest, there has been damage to a vena comitans of the DIEP pedicle,

then one would expect that the venous insult should affect the whole flap and be due to inadequate total venous return, not partial.³⁴ Furthermore, inadequate venous drainage causes rapid capillary refill, not sluggish. Because the venous system is typically redundant (veins are always larger than their accompanying artery, and often duplicate), it is not logical to suggest that part of a flap may have “venous insufficiency” in our opinion. It is sensible to consider an alternative, more physiological, explanation for the same observation. Peripheral arterial input insufficiency affecting distal parts of a flap may result in small amounts of blood flowing sluggishly into the capillary system where oxygen desaturation causes a darker color. This would also be manifest as sluggish capillary return. This is commonly seen in zone 4 of raised DIEP flaps before that zone is removed. It is our contention that this phenomenon represents arterial insufficiency with partial flap necrosis occurring as a result of inadequate oxygen delivery. Suboptimal oxygenation of blood in the periphery of the flap yields the color and flow changes, not “venous insufficiency” occurring in a poorly drained area of the flap. In single-perforator DIEP flaps, the primary mechanism leading to partial flap necrosis is arterial insufficiency, and the most important factor affecting flow rates is perforator size.

CONCLUSIONS

Correlation of the absolute findings of this study with others supports the concept of a safe level of absolute blood flow which will nourish a certain weight of free flap tissue without any flap necrosis. Our study has shown that absolute blood flow through the flap pedicle is most significantly correlated with the perforator diameter. Flap weight is also correlated but to a lesser extent. As with any clinical scenario, there are other variables such as position of any given perforator within the flap. The FVI ratio is an empirically derived equation that seeks to take all of these variables into account, combining the 2 major modifiable variables, perforator diameter and flap weight, to help predict the safe level of blood flow required to fully perfuse the flap. None of the patients in this study group underwent any flap necrosis, and in fact, since routinely ensuring FVI values greater than 10, we have had no flap necrosis in any of our DIEP flaps. Utilization of the FVI equation for free-flap planning and intraoperative decision making is a valid method for ensuring complete flap survival.

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