A Theoretical Model Describing the Dynamics of Venous Flow in the DIEP Flap

Murad J. Karadsheh, MD[1] M. Shuja Shafqat, MD[2,3] James C. Krupp, MD[1] Eric S. Weiss, MD[1]
Sameer A. Patel, MD, FACS[1,2,3]

[1] Department of Surgery, Einstein Healthcare Network, Philadelphia, Pennsylvania
[2] Department of Surgery, Division of Plastic and Reconstructive Surgery, Temple University Hospital, Philadelphia, Pennsylvania
[3] Department of Surgical Oncology, Division of Plastic and Reconstructive Surgery, Fox Chase Cancer Center, Philadelphia, Pennsylvania

Address for correspondence Sameer A. Patel, MD, FACS, Division of Plastic and Reconstructive Surgery, Department of Surgical Oncology, Temple University Hospital Plastic Surgery Residency, Fox Chase Cancer Center, 333 Cottman Avenue, Philadelphia, PA 19111 (e-mail: sameer.patel@fccc.edu).

J Reconstr Microsurg 2019;35:688–694.

Abstract

Background The deep inferior epigastric artery flap is an integral component of autologous breast reconstruction. The technical aspects of performing the flap have been well-established. A prior mathematical model suggested using the largest perforator and concluded that the inclusion of additional perforators may decrease resistance and increase flow, but at the downside of increased tissue trauma. Many complications may result from inadequate venous drainage of the flap and the same mathematical concepts may be applied. We attempt to give a mathematical model, based on the physics of flow and properties of circuits, to explain clinical observations regarding venous drainage of the flap and the complications that may arise.

Methods We compare the different possible venous drainage systems of a perforator flap to a complex circuit with multiple resistances. Multiple venous perforators will be represented by resistances in parallel, while the deep and superficial drainage systems will be represented by a complex circuit loop.

Results Drainage of the flap may be optimized through the deep drainage system if the venous perforators are of sufficient size. Inclusion of additional perforators may decrease resistance and enhance drainage. Salvage procedures may be necessary when the venous perforators are insufficient in size or when there are insufficient connections between the deep and superficial systems.

Conclusion A single large sized vessel may provide adequate drainage in most DIEP flaps, while the use of multiple vessels may enhance drainage upon the encounter of smaller vessels. Salvage procedures may be needed to relieve venous congestion as the design of the venous system becomes more complicated.

Keywords
- breast reconstruction
- blood flow
- deep inferior epigastric artery perforator flap
- venous congestion
- fat necrosis
- myocutaneous
- venous perforator

The deep inferior epigastric perforator (DIEP) flap use in reconstruction was first described in 1989 by Koshima and Soeda,[1] and popularized by Allen[2] in 1994 for breast reconstruction. Since then, it has become one of the most preferred and integral components in the field of autologous breast reconstruction. The technical aspects of performing a DIEP flap have been modified and well-established over the years. However, the literature regarding the impact of perforator number and size on flap viability remains variable. Blondeel et al[3] advocated the use of larger caliber perforators and inscription vessels and argued that the distance of the perforator from the midline determines flap viability as opposed to the number of perforators. Gill et al[4] found that the complication rate was higher as more perforators

received
January 20, 2019
accepted after revision
June 4, 2019
published online
July 30, 2019

DOI https://doi.org/10.1055/s-0039-1693692.
ISSN 0743-684X.

were recruited, while Grover et al[5] found that the number of perforators does not impact flap survival. However, it is generally acceptable to use a single centrally located perforator of large caliber (1.5 mm). If no such dominant perforator exists, then multiple (2–4) medium-sized (1 mm) perforators may be dissected from the medial or lateral row.[5]

Patel et al[6] developed a theoretical model to describe the arterial flow in the DIEP flap and explain the clinical observations described above, based on the physics of flow through vessels and the properties of circuits with multiple resistances in parallel. This model supports the use of a single large diameter vessel. While inclusion of additional smaller perforators may theoretically reduce overall resistance, this is dependent on the diameter of the additional perforators and may come with the cost of additional trauma to the muscle and fascia. However, while arterial flow in the DIEP flap is important, flap survival also depends on adequate venous drainage. The rate of venous congestion is reported to be between 2–8% and is associated with increased flap complications and potential failure.[7,8] Additionally, the same rules that govern flow through the arterial system apply to the venous system, therefore, a similar theoretical model may be more clinically relevant if applied to the venous drainage of the flap. In this article, we attempt to provide a mathematical explanation, based on the physics of flow through vessels and the properties of circuits to describe the venous circulation in the DIEP flap.

Methods

We compare a system of multiple venous perforators to a circuit with multiple resistances. The venous drainage of the DIEP occurs via two main pathways: the superficial and deep inferior epigastric veins.[9–12] The superficial and deep venous systems have extensive anastomotic connections by a network of linking veins.[9–14] In most cases, the DIEP flap is primarily drained via venous perforators from the deep inferior epigastric veins (DIEV) and main pedicle.[9,15] The DIEV are often paired veins that have ladder-like (H-type) connections and usually unite prior to drainage into the external iliac vein.[9,13] The superficial system normally drains into the superficial epigastric vein in a nonsurgical patient.[8] However, after isolation of the DIEP flap, the superficial inferior epigastric vein (SIEV) is transected and flow will be redirected into the deep system via the network of linking veins.[8,12] The superficial system may be dominant in cases when the deep perforator veins are insufficient in diameter.[9,12,13] Additionally, the superficial system may be of greater importance when linking veins are insufficient or absent between the two systems.[12,13] A typical DIEP flap venous system will be represented by ►Fig. 1, which includes a single venous perforator in series with a network of veins composed of the superficial and deep drainage systems that are connected by the linking veins. This figure is based on a dominant deep venous drainage system and a single DIEP perforating artery. As previously mentioned, there are multiple bridging connections between the DIEV, which will not be represented in our model for simplicity.

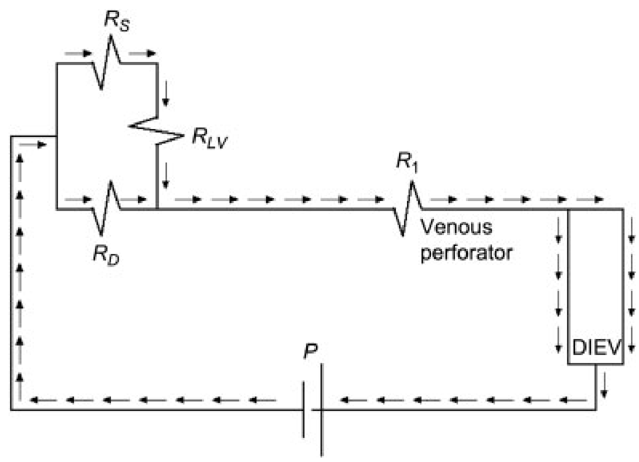

Fig. 1 Circuit representing typical DIEP flap with dominant deep venous system with drainage via a single venous perforator with resistance R_1. The arrows represent the normal direction of flow. (P, pressure; R_D, resistance of the deep venous system; R_S, resistance of the superficial venous system; R_{LV}, resistance of the linking veins; DIEV, deep inferior epigastric vein).

Additionally, secondary drainage may occur through the SIEV, superior epigastric vein, superficial circumflex iliac vein, and lower intercostals.[15] However, with the exception of the SIEV, these are not included in the flap, therefore will not be included in our model for simplicity.

In a flap with multiple arterial perforators, each additional perforating artery will be paired with a venous perforator. These perforating veins will be in parallel configuration with each other. Additionally, this system of parallel veins will be in series with the venous plexus draining the flap.

The resistance through a tube is defined by the following equation:

$$R = \frac{8nL}{(\pi)r^4} \quad (1)$$

where R is resistance, n is a constant, L is the length of the vessel, and r is the radius of the vessel.

For multiple resistors in parallel, the total resistance R_t is defined as follows:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_n} \quad (2)$$

where n equals the total number of perforator vessels.

Ohm's Law states that current (I) is equal to the change in voltage (ΔV) divided by the resistance (R) or:

$$I = \Delta V/R$$

When applied to hemodynamics, this law tells us that flow is inversely proportional to resistance:

$$F = \frac{\Delta P}{R} = \frac{(P_a - P_V)}{R}$$

where P_a is the arterial pressure and P_v is the venous pressure. The difference gives the pressure gradient. Therefore, the lower the resistance, the higher the flow, and vice versa.

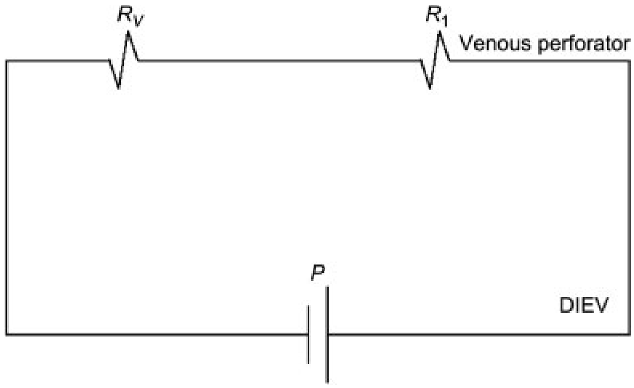

Fig. 2 Circuit representing drainage via a single venous perforator with resistance R_1. (*P*, inflow pressure; R_V, combined resistance of the superficial system, deep system, and linking veins; DIEV, deep inferior epigastric vein).

Results

The simplest case of outflow for the DIEP flap is one based on a DIEV dominant drainage system with a single venous perforator of length L_1 and radius r_1 (►**Fig. 2**). This model also assumes there is sufficient communication between the superficial and deep venous systems. For simplicity, the superficial venous network, deep venous network, and the linking veins will be represented by a single combined resistance (R_V). Based on this model, the resistance R_1 generated by the perforator vessel is:

$$R_1 = 8nL_1/(\pi)r_1{}^4$$

In this case, the shorter the vessel and the greater the diameter, the lower resistance and the greater the flow.

However, in a DIEP flap with multiple perforating arteries, each artery is paired with a venous perforator. Therefore, a flap design with two perforating arteries will have two venous perforators in parallel configuration. In this scenario, if the two venous perforators have the same resistance as the single vessel in the first scenario (r_1 and L_1) in a DIEV dominant drainage system (►**Fig. 3**), the total resistance of the perforators taken together changes according to Eq. (2). The total resistance (R_t), in this case will be equal to half of the resistance seen in the first scenario, or ($1/2R_t$). This should theoretically increase the outflow from the flap.

If two venous perforators with radii (r_2) smaller than (r_1) were used (►**Fig. 4**) instead of the single perforator with radius r_1, this should theoretically increase the resistance according to Eq. (2). Consider a scenario with two perforators each with a radius (r_2) that is half of (r_1), or $r_2 = (1/2)\, r_1$. The resistance of each perforator will be $16 \times R_1$ according to Eq. 1. The total resistance generated by using the two smaller vessels with radius (r_2) as determined by Eq. 2 will be equal to eight times the value of R_1.

Moreover, this concept can be applied to a flap model with more than two perforators. For example, consider a flap with a total of four venous perforators in parallel. In this case, if each venous perforator has the same radius (r_1), as in the first scenario, the total resistance will decrease by 75% according to Eq. 2. However, in this same flap design, if each venous perforator has a radius (r_2), half of (r_1), with resulting resistance of $16 \times R_1$ for each perforator, the total resistance will increase by a factor of 4.

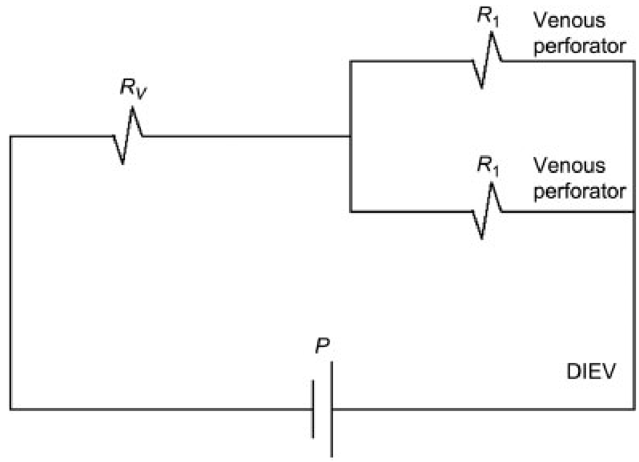

Fig. 3 Circuit representing drainage via two perforating deep veins of same resistance as perforator in ►**Fig. 1** (R_1). (*P*, pressure; R_V, combined resistance of the superficial system, deep system, and linking veins; DIEV, deep inferior epigastric vein).

Upon closer review of the two previously discussed scenarios, it can be observed that there exists a point at which the use of two smaller vessels becomes a limitation to flow as opposed to using a single larger vessel, as determined in the arterial model by Patel et al.[6] In one case, a single vessel with a radius (r_1) is used. In another case, two vessels are used, one with radius (r_2) and the other with radius (r_3). Therefore, in order for the resistances in each case to be the same, the following must occur:

$$r^4{}_1 = r^4{}_2 + r^4{}_3 \qquad (3)$$

According to this equation, if the two smaller vessels have the same radii, the point at which the two smaller vessels have

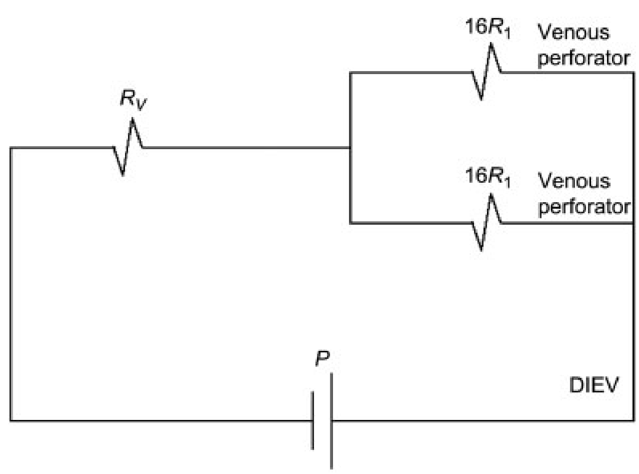

Fig. 4 Circuit representing drainage via two perforating deep veins with radii equal to half of the radii of perforators in ►**Figs. 2** and **3**, therefore with resistances 16 times that of resistance of R_1. (*P*, pressure; R_V, combined resistance of the superficial system, deep system, and linking veins; DIEV, deep inferior epigastric vein).

the same resistance as the single larger vessel occurs when the smaller radii are the fourth root of 1/2 or approximately 0.84 times the radius of the single larger vessel. Therefore, if the vessels are larger than 0.84 r_1, then the flow would be greater using the smaller perforators. If the vessels are smaller than 0.84 r_1, then the flow would greater using a single larger perforator. In general, if n vessels of equal but smaller radii than a single larger vessels are used, the resistances of the two systems will be equal when the radii of the smaller vessels are the fourth root of $1/n$ times the radius of (r_1). For example, if three smaller perforators are used instead of a single larger perforator, the resistances of the two perforator systems will be equal when the radii of the smaller perforators are the fourth root of 1/3, or 0.76 times the radius of the single perforator.

This concept may explain drainage in a flap with a dominant superficial drainage system. If a SIEV with radius r_{SIEV} and resistance R_{SIEV} is encountered in a flap with two venous perforators from the deep system, then it will be the dominant drainage system if the two venous perforators are less than 0.84 times the radius of the SIEV, or 0.84 r_{SIEV}. The resistance across each individual venous perforator with radius 0.84 r_{SIEV} or less will be at least double the resistance of the SIEV (R_{SIEV}), or $2R_{SIEV}$. Most of the venous outflow, or drainage of the flap will be directed towards the path of least resistance through the superficial venous system in a nonsurgical patient. However, since the SIEV is transected with flap dissection, therefore, interrupting flow across the superficial system, flap drainage will be redirected towards the perforating veins of the DIEV via the linking veins (►**Fig. 5**). This will theoretically hinder flap drainage as flow will be forced across the high resistance of the deep system, which may contribute to venous congestion. One proposed technique to salvage intraoperative venous congestion is by supercharging the flap. Supercharging involves providing additional outflow by anastomosing the SIEV to a recipient vein such as the cephalic or thoracodorsal, or an additional internal mammary vein (►**Fig. 6**).[7] This allows most of the drainage to flow through the low-resistance superficial system.

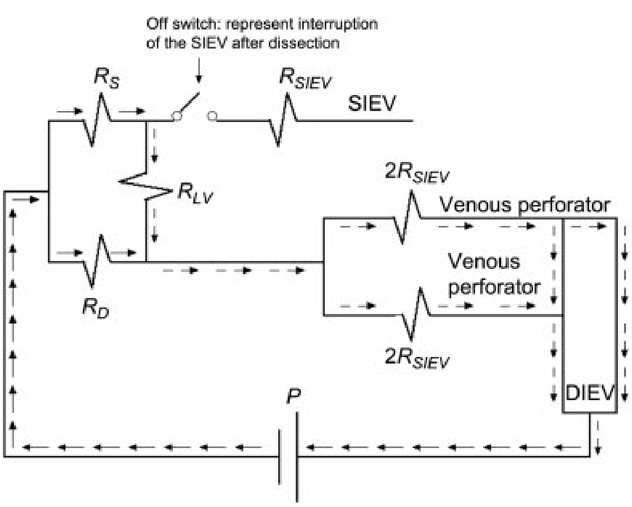

Fig. 5 Circuit representing drainage via two perforating veins from the deep system with radii 0.84 times the radius of the SIEV. The solid black arrows represent the normal direction of flow through the path of least resistance of the superficial drainage system. The dashed arrows represent the resulting redistribution of flow across the high-resistance deep system after ligation of the SIEV. (P, pressure; R_D, resistance of the deep system; R_S, resistance of the superficial system; R_{LV}, resistance of the linking veins; R_{SIEV}, resistance of the SIEV; SIEV, superficial inferior epigastric vein; DIEV, deep inferior epigastric vein).

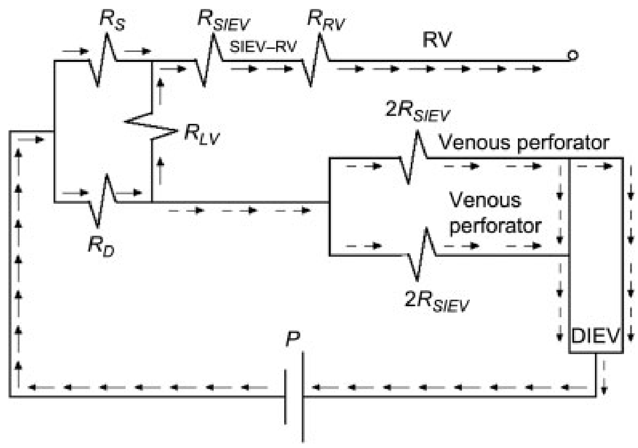

Fig. 6 Supercharged flap with two perforating veins off the deep system with radii 0.84 times the radius of the SIEV. The SIEV is anastomosed to a recipient vessel. Most of the flow will now be directed towards the low-resistance superficial system (solid arrows). The dashed arrows represent residual flow through the high-resistance deep system. (P, pressure; R_D, resistance of the deep system R_S, resistance of the superficial system; R_{LV}, resistance of the linking veins; R_{SIEV}, resistance of the SIEV; R_{RV}, resistance of the recipient vessel; RV, recipient vessel; SIEV, superficial inferior epigastric vein; DIEV, deep inferior epigastric vein).

In a scenario where the venous perforators are of sufficient size (r_1) but with insufficient or absent connections between the superficial and deep systems, flap drainage may also be hindered as outflow from the superficial system would be obstructed (►**Fig. 7**). Turbocharging is another method to salvage venous congestion, which involves creating a superficial to deep venous loop by anastomosing the SIEV to one of the DIEV (►**Fig. 8**).[7]

However, according to our model, turbocharging the flap may not be effective in a flap with a high-resistance deep system, as in a case where the DIEV have radii of 0.84 r_{SIEV}. In this scenario, drainage would be redirected towards the high-resistance deep system and may not relieve venous congestion. Clinically, this indicates that if intraoperative venous congestion does occur, the better maneuver is to anastomose the SIEV to a different outflow vein rather than a pedicle branch.

If a single vessel with the largest diameter has been incorporated in the perforator flap, the addition of smaller vessels during dissection would theoretically reduce the total resistance of the perforator system according to Eq. 2. This relationship can be described by combining Eqs. (1), (2), and (3) as follows:

$R_2 = R_1\ [1/(1 + x^4)]$, where R_2 is the resistance of the system when a second vessel of radius xr_1 is added to the single vessel of radius r_1 with resistance R_1. If two additional

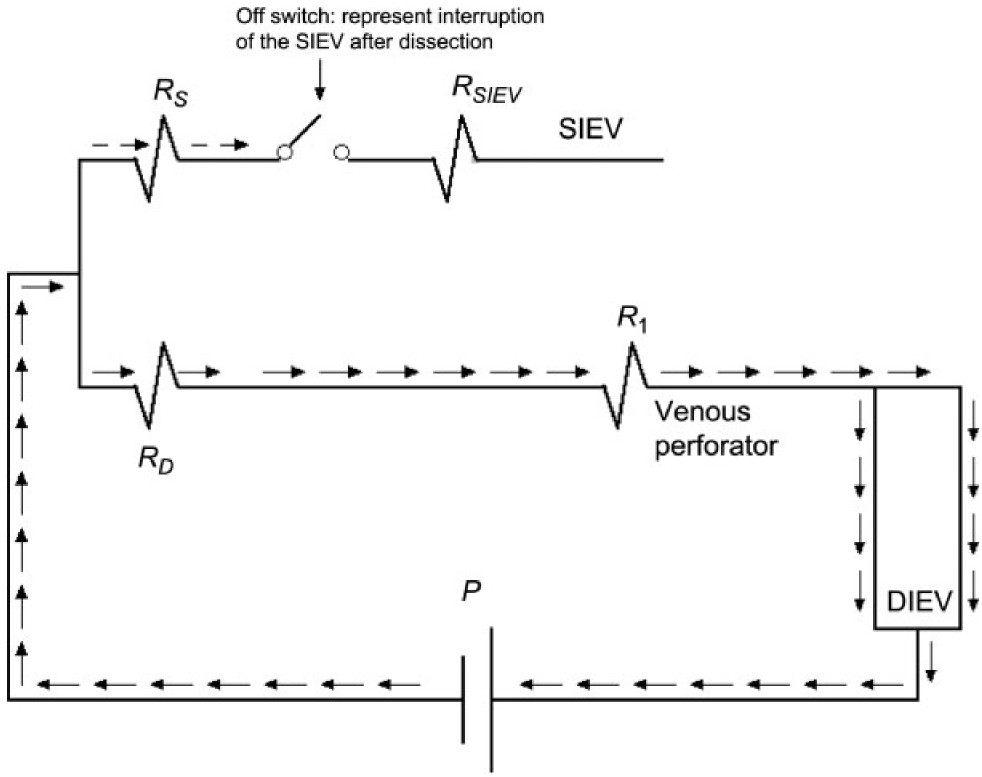

Fig. 7 Circuit representing drainage via a single venous perforator off the deep system with resistance R_1. The solid black arrows represent the normal direction of flow through the deep system. The dashed arrows represent obstructed flow through superficial system. (*P*, pressure; R_D, resistance of the deep system; R_S, resistance of the superficial system; R_{SIEV}, resistance of the SIEV; SIEV, superficial inferior epigastric vein; DIEV, deep inferior epigastric vein).

vessels with radii of xr_1 and yr_1 are added to the single vessel, the resistance of the system of three vessels R_3 would be as follows:

$R_3 = R_1\ [1/(1 + x^4 + y^4)]$

According to this equation, adding a second vessel with a diameter of 0.9 times, the single larger vessel will decrease the resistance to approximately 0.6 times the resistance of the single large vessel. However, adding a second vessel with a diameter of 0.5 times the single larger vessel will result in a decrease in resistance only approximately 1/10th, or 0.9 times the resistance of the single larger vessel.

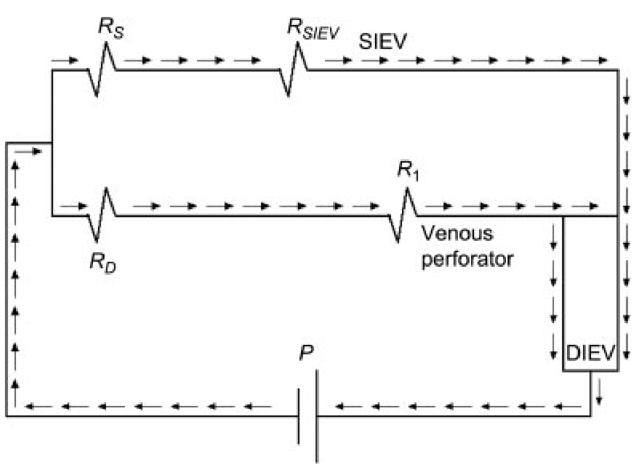

Fig. 8 Turbocharged model representing drainage via a single venous perforator with resistance R_1. The solid black arrows represent the normal direction of flow. (*P*, pressure; R_D, resistance of the deep system; R_S, resistance of the superficial system; R_{LV}, resistance of the linking veins; R_{SIEV}, resistance of the SIEV; SIEV, superficial inferior epigastric vein; DIEV, deep inferior epigastric vein).

If two equal sized venous perforators of largest diameter have been incorporated, the addition of smaller single venous perforator would also reduce the total resistance. This relationship can be described by the following equation:

$R_2 = R_1\ [1/(2 + x^4)]$ where R_2 is the resistance of a system with two equal sized venous perforators when a third venous perforator of radius xr_1 is added to the system with resistance R_1.

According to the above equation, in a perforator system with two equal sized perforators, the addition of a third venous perforator with a diameter of 0.9 times, the diameter of one of the larger venous perforator will decrease the resistance to approximately 0.38 times the resistance of the two larger venous perforators.

Discussion

Several studies have described the perfusion to the infraumbilical abdominal wall and, hence, the DIEP flap. Adequate perfusion of the flap is crucial for flap survival and to minimize complications such as fat necrosis, arterial thrombosis, and venous congestion. Such complications may lead to increased flap morbidity and flap loss. Therefore, methods to minimize these complications should be applied.

One method to minimize complications may include the use of multiple arterial perforators. In the model described by Patel et al,[6] the inclusion of additional perforators may decrease resistance and enhance perfusion of the flap. This may ultimately minimize certain complications, such as fat necrosis, which has an incidence between 5 to 35%.[16] Fat necrosis is a significant sequelae of the DIEP flap as it can create wound healing complications and wound infections. In addition, these firm masses can cause significant distress to the breast cancer patient and increase the risk of additional imaging, biopsies, and surgery. In the current literature, there is a lower incidence of fat necrosis with a higher number of perforators.[16] However, a higher incidence of fat necrosis has been observed with the use of several perforators, notably five or more.[4,16] This may be due to increased tissue trauma from additional dissection of the flap and the lack of a strong central blood supply in instances where there are multiple small-diameter vessels. Additionally, some studies reported an increased rate of fat necrosis in the setting of venous congestion and that fat necrosis may be mitigated in by augmentation of venous outflow.[8,17,18]

While arterial perfusion remains an important component of the DIEP flap, venous drainage may be more clinically relevant as inadequate venous drainage may result in venous congestion and potential failure of the flap. The incidence of venous congestion in DIEP flaps is reported to be 2 to 8%.[8] An inadequate venous drainage system leading to venous congestion will result in an increase in venous pressure and edema across the flap.[19] This rise in pressure of the obstructed venous system may transmit to the arterial system potentially impairing inflow. Impaired arterial inflow may be further exacerbated by the resulting arterial thrombosis that may occur. This may further damage the flap and impair its survival. The cause of venous congestion is multifactorial. This may be a result of venous thrombosis, insufficient communications between the deep and superficial venous system, or small caliber venous perforators. External causes include inadequate inflow from poor perforator selection, vessel kinking, or anastomotic failure with recipient vessels.[20,21] Blondeel et al suggested that it is failure of venous outflow as opposed to arterial inflow that is the rate-limiting step in flap survival, as demonstrated by bluish discoloration of the flap and dark venous bleeding when venous congestion occcurs.[12]

Large caliber venous perforators may be adequate for drainage of a DIEP flap, given a dominant deep drainage system. Some literature suggests a single 2 mm vein to be of adequate size.[5] Based on our model, the inclusion of additional perforator veins may decrease resistance and therefore enhance outflow of the DIEP flap. If a vein less than 2 mm is encountered, our model supports the use of multiple venous perforators to decrease resistance and enhance drainage. However, outflow may be limited when the size of the venous perforator is small or when the size of the SIEV becomes important.

A flap may have a dominant superficial drainage system when the SIEV size is large. Current literature suggests that intraoperative venous congestion is observed with a SIEV diameter of 1.5 mm or greater.[5] In this scenario, according to our model, a deep system with two venous perforators may only adequately drain the flap if the venous perforators are greater than 1.26 mm in diameter as determined by Eq. 3. If venous perforators of smaller size are encountered, the risk of intraoperative venous congestion increases and a salvage procedure may be necessary. Therefore, it is recommended that the SIEV be preserved in all situations until the size of the deep venous perforators can be assessed.

Supercharging may relieve intraoperative venous congestion by allowing drainage of the flap through the SIEV instead of forcing outflow through the high-resistance deep system. The SIEV, in this situation, may be anastomosed to the cephalic vein, thoracodorsal vein, or an additional internal mammary vein. Turbocharging is another technique to salvage the flap. This involves anastomosing the SIEV to a branch of the deep system. This technique may be useful when the deep system alone is inadequate for drainage and in situations where there are insufficient connections between the superficial and deep drainage systems. However, this would not be effective in flaps with SIEV dominant drainage and small caliber venous perforators where the resistance of the deep system is high and would still not provide adequate outflow.

The clinical application of this study can be difficult when a simplified version of a complex system is used. However, there are some takeaway points based on this model alone. When dissecting a DIEP flap, it is prudent to preserve the SIEV and dissect it for several centimeters in all scenarios until the caliber of the venous perforators can be assessed. This allows a lifeboat in the event of small venous perforators from the deep system. Turbocharging the flap may be effective in certain scenarios where the linking veins between the superficial system and the deep system are inadequate but would not be effective if the resistance in the deep system is high. Therefore, it seems safe to always supercharge these flaps if necessary rather than turbocharge them. The dominant perforator should always be sought, especially the one with the largest vein. This supersedes taking multiple small perforators to compensate for the large one, unless the smaller perforators are of adequate size where they do not limit outflow from the flap. The dominant perforator can be harvested with additional perforators from the same row to decrease overall resistance.

The limitations of this study are mostly a result of a theoretical model that is simplified, applied to a complex system that is highly variable. There are physiologic factors that can cause the radius of the vessels to contract such as hypoxia, manipulation, hypothermia, and a variety of other reasons. In addition, the radius of the outflow is not constant across the entire system from the subdermal plexus to the perforator, to the DIEV in the main pedicle.

In conclusion, maintaining adequate perfusion and drainage of the DIEP flap are crucial to its survival. Adequate perfusion may be achieved with a single large sized vessel in most DIEP flaps. However, upon encounter of smaller vessels, it would be beneficial to include multiple perforators as this can reduce resistance and enhance flow. This concept also applies to the venous system as the addition of multiple vessels may also reduce resistance and enhance drainage.

However, additional measures may be needed in order to relieve venous congestion and prevent flap loss as the design of the venous system becomes more complicated. Further clinical observations and analysis should be taken to confirm this theoretical model.

Conflict of Interest
None declared.

References

1 Koshima I, Soeda S. Inferior epigastric artery skin flaps without rectus abdominis muscle. Br J Plast Surg 1989;42(06):645–648
2 Allen RJ, Treece P. Deep inferior epigastric perforator flap for breast reconstruction. Ann Plast Surg 1994;32(01):32–38
3 Blondeel PN. One hundred free DIEP flap breast reconstructions: a personal experience. Br J Plast Surg 1999;52(02):104–111
4 Gill PS, Hunt JP, Guerra AB, et al. A 10-year retrospective review of 758 DIEP flaps for breast reconstruction. Plast Reconstr Surg 2004;113(04):1153–1160
5 Grover R, Nelson JA, Fischer JP, Kovach SJ, Serletti JM, Wu LC. The impact of perforator number on deep inferior epigastric perforator flap breast reconstruction. Arch Plast Surg 2014;41(01):63–70
6 Patel SA, Keller A. A theoretical model describing arterial flow in the DIEP flap related to number and size of perforator vessels. J Plast Reconstr Aesthet Surg 2008;61(11):1316–1320, discussion 1320
7 Kim D-Y, Lee TJ, Kim EK, Yun J, Eom JS. Intraoperative venous congestion in free transverse rectus abdominis musculocutaneous and deep inferior epigastric artery perforator flaps during breast reconstruction: a systematic review. Plast Surg (Oakv) 2015;23(04):255–259
8 Ochoa O, Pisano S, Chrysopoulo M, Ledoux P, Arishita G, Nastala C. Salvage of intraoperative deep inferior epigastric perforator flap venous congestion with augmentation of venous outflow: flap morbidity and review of the literature. Plast Reconstr Surg Glob Open 2013;1(07):e52
9 Gagnon AR, Blondeel PN. Deep and Superficial Inferior Epigastric Artery Perforator Flaps. In: Wei FC, Mardini S, editors. Flaps and Reconstructive Surgery. Philadelphia, PA: Elsevier; 2009:668–686
10 Dortch J, Forte AJ, Bolan C, Kandel P, Perdikis G. Preoperative analysis of venous anatomy before deep inferior epigastric perforator free-flap breast reconstruction using ferumoxytol-enhanced magnetic resonance angiography. Ann Plast Surg 2018. Doi: 10.1097/SAP.0000000000001421
11 Schaverien M, Saint-Cyr M, Arbique G, Brown SA. Arterial and venous anatomies of the deep inferior epigastric perforator and superficial inferior epigastric artery flaps. Plast Reconstr Surg 2008;121(06):1909–1919
12 Blondeel PN, Arnstein M, Verstraete K, et al. Venous congestion and blood flow in free transverse rectus abdominis myocutaneous and deep inferior epigastric perforator flaps. Plast Reconstr Surg 2000;106(06):1295–1299
13 Rozen WM, Pan WR, Le Roux CM, Taylor GI, Ashton MW. The venous anatomy of the anterior abdominal wall: an anatomical and clinical study. Plast Reconstr Surg 2009;124(03):848–853
14 Taylor GI. The blood supply of the skin. In: Aston SJ, Beasly RW, Thorne CH, et al. Grabb and Smith's Plastic Surgery. 5th ed. Philadelphia, PA: Lippincott-Raven; 1997:47–59
15 Gagnon A, Blondeell P. Deep and superficial inferior epigastric artery perforator flaps. Cirugía Plástica Ibero-Latinoamericana 2006;32(04):1–7
16 Baumann DP, Lin HY, Chevray PM. Perforator number predicts fat necrosis in a prospective analysis of breast reconstruction with free TRAM, DIEP, and SIEA flaps. Plast Reconstr Surg 2010;125 (05):1335–1341
17 Kroll SS. Fat necrosis in free transverse rectus abdominis myocutaneous and deep inferior epigastric perforator flaps. Plast Reconstr Surg 2000;106(03):576–583
18 Ali R, Bernier C, Lin YT, et al. Surgical strategies to salvage the venous compromised deep inferior epigastric perforator flap. Ann Plast Surg 2010;65(04):398–406
19 Enajat M, Rozen WM, Whitaker IS, Smit JM, Acosta R. A single center comparison of one versus two venous anastomoses in 564 consecutive DIEP flaps: investigating the effect on venous congestion and flap survival. Microsurgery 2010;30(03): 185–191
20 Bartlett EL, Zavlin D, Menn ZK, Spiegel AJ. Algorithmic approach for intraoperative salvage of venous congestion in DIEP flaps. J Reconstr Microsurg 2018;34(06):404–412
21 Schaverien MV, Ludman CN, Neil-Dwyer J, et al. Relationship between venous congestion and intraflap venous anatomy in DIEP flaps using contrast-enhanced magnetic resonance angiography. Plast Reconstr Surg 2010;126(02):385–392