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# A theoretical model describing arterial flow in the DIEP flap related to number and size of perforator vessels

Sameer A. Patel <sup>a,\*</sup>, Alex Keller <sup>b</sup>

<sup>a</sup> Fox Chase Cancer Center, Philadelphia, PA, USA

<sup>b</sup> North Shore Long Island Jewish Health System, New Hyde Park, NY, USA

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**Summary** *Background:* The deep inferior epigastric perforator flap is rapidly becoming a more widely employed method of autologous breast reconstruction. The technical considerations involved in the execution of the flap are many and include the selection of perforators to be incorporated in the flap. We attempt to give a mathematical explanation, based on the physics of flow through vessels and the properties of circuits with multiple resistances in parallel, for the clinical observations which have been arrived at through clinical experience. *Methods:* We compare the system of perforators to a circuit with multiple resistances in parallel. Each of these resistances represents a perforator vessel. In the event that there is only one perforator vessel, this simplifies to a single resistance in series with the capillary bed perfusing the flap.

*Results:* The flow through the flap is optimized by incorporation of the largest diameter perforator. Inclusion of other smaller perforators in addition to the largest diameter perforator will reduce the overall resistance, but this reduction in resistance is dependent on the diameter of the additional perforator and may not be worth the additional trauma of dissection and increased operative time. Incorporating several smaller perforators at the expense of excluding the largest diameter perforator appears to increase the overall resistance, unless the smaller perforators are only slightly smaller.

*Conclusions:* We conclude that the best perfused flap involves use of the largest diameter vessel, that although adding additional perforators will decrease the resistance and increase flow, the magnitude of the benefit depends largely on the calibre of the additional perforator, and that this benefit needs to be weighed against the downside of increased muscle and facials trauma.

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\* Corresponding author. Address: Fox Chase Cancer Center, Plastic and Reconstructive Surgery, 333 Cottman Avenue, Philadelphia, PA 19111, USA. Tel.: +1 646 713 6773.

E-mail address: [sameer.patel.md@gmail.com](mailto:sameer.patel.md@gmail.com) (S.A. Patel).

Since the original description of the deep inferior epigastric perforator (DIEP) flap for use in reconstruction was published by Koshima and Soeda,<sup>1</sup> the flap has rapidly become an integral component in the field of autologous breast reconstruction. The role of the DIEP flap, and perforator flaps in general, in reconstructive surgery is becoming more defined. The technical aspects of performing perforator flaps have largely been set forth by the personal experience of those surgeons that perform them routinely. Although there are several aspects to performing DIEP flaps that have become accepted based on these personal experiences, such as the use of the largest perforator<sup>2,3</sup> as well as a preference for inscription vessels,<sup>4</sup> no theoretical explanation has been proposed to either support or refute them. In particular, the choice of which perforator vessels to select, the ideal number of perforator vessels to include, and the impact that the diameter and length of these vessels has on the perfusion of the flap are largely based on personal experiences guided by knowledge of the anatomy of the blood supply to the abdominal wall. In this article, we attempt to give a mathematical explanation, based on the physics of flow through vessels and the properties of circuits with multiple resistances in parallel, for the clinical observations which have been arrived at through clinical experience.

## Methods

We compare the system of perforators to a circuit with multiple resistances in parallel. Each of these resistances represents a perforator vessel. In the event that there is only one perforator vessel, this simplifies to a single resistance in series with the capillary bed perfusing the flap.

With multiple perforators, each perforator vessel is in a parallel configuration with each of the other perforator vessels. In this case, we assume this system of parallel vessels is in series with the capillary bed, an assumption based on current knowledge of angiosomes and the choke anastomoses which interconnect adjacent territories.<sup>5</sup>

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

$$R = 8nl / (\pi)r^4 \quad (1)$$

<sup>6</sup>where  $R$  is resistance,  $n$  is a constant,  $l$  is the length of the vessel, and  $r$  is the radius of the vessel.

The total resistance ( $R_t$ ) of multiple resistors in parallel is defined as follows:

$$1/R_t = 1/R_1 + 1/R_2 + 1/R_3 + \dots + 1/R_n \quad (2)$$

<sup>6</sup>where  $n$  is the total number of perforator vessels.

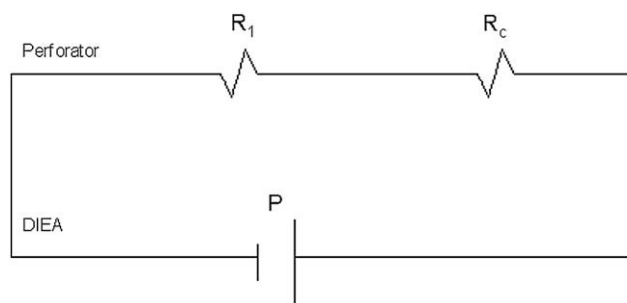
Flow is related to resistance by the following equation:

$$\text{Flow} = \text{Pressure} / \text{Resistance}.$$

## Results

The simplest case of inflow for the DIEP flap is a single perforator with a length  $L_1$  and a radius  $r_1$  (Figure 1). In this case, the resistance  $R_1$  generated by the perforator vessel is:

$$R_1 = 8n_1 L_1 / \pi r_1^4$$

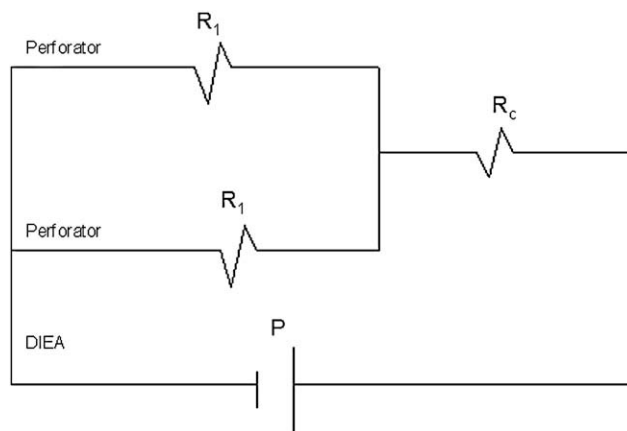


**Figure 1** Circuit representing single perforator with resistance  $R_1$  ( $R_c$ , capillary resistance;  $P$ , pressure; DIEA, deep inferior epigastric artery).

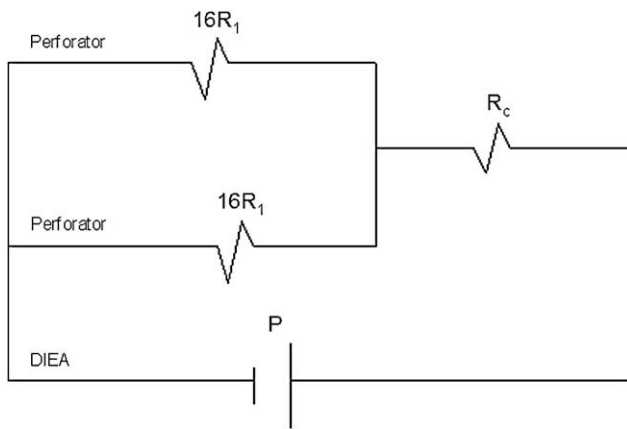
Clearly in this case, the shorter the vessel and the greater the diameter, the lower the resistance and the greater the flow.

If a flap design with two perforators with the same resistance as the single vessel in the first scenario ( $r_1$  and  $L_1$ ) is considered (Figure 2), the total resistance of these perforators taken together changes. This relationship is defined by Eq. (2) above. The total resistance in this case,  $R_t$ , is half of the resistance seen in the first scenario 1, or  $1/2 R_1$ . The conclusion that can be made is that if two vessels of the same radius and length as the single perforator are encountered, the total resistance will be decreased by 50% if two perforators are used in the design of the perforator flap. This should theoretically double the flow to the flap.

This raises an interesting question. What would happen if two perforators with radii ( $r_2$ ) smaller than  $r_1$  were used instead of the single perforator with radius  $r_1$  (Figure 3)? Assume a scenario with two perforators each with a radius ( $r_2$ ) half of  $r_1$ . Mathematically, this can be stated  $r_2 = (1/2)r_1$ . The resistance of each perforator will be  $16 R_1$ . If the resistance of this system of perforator vessels is determined using Eq. (2), the total resistance generated by using two smaller vessels each with a radius of half of a larger single perforator with radius



**Figure 2** Circuit representing two perforators of same resistance as perforator in Figure 1 ( $R_1$ ) ( $R_c$ , capillary resistance;  $P$ , pressure; DIEA, deep inferior epigastric artery).



**Figure 3** Circuit representing two perforators with radii equal to half of the radii of perforators in Figures 1 and 2, and therefore with resistances 16 times that of the resistance  $R_1$  ( $R_c$ , capillary resistance;  $P$ , pressure; DIEA, deep inferior epigastric artery).

$r_1$  and resistance  $R_1$  can be shown to equal eight times the value of  $R_1$ .

If the two previously discussed scenarios are studied more carefully, there exists some point at which the use of two smaller perforators becomes a limitation to flow as opposed to using a single larger perforator. In one case, only a single perforator with a radius  $r_1$  is used. In the second case, two perforators are used, one with radius  $r_2$  and the other with radius of  $r_3$ . In order for the total resistances generated by the perforators to be the same in each case, the following has to occur:

$$r_1^4 = r_2^4 + r_3^4 \quad (3)$$

Using this equation and assuming that the two smaller perforators have the same radii, the point at which the two smaller perforators have the same resistance as the single larger perforator vessel occurs at a point where the smaller radii are (the fourth root of 1/2) times the radius of the single perforator, or approximately 0.84 times the radius of the single larger perforator vessel. If the vessels are larger than  $0.84r_1$ , then the flow would be greater using the smaller perforators. If the perforators are smaller than  $0.84r_1$ , then the flow would be greater using the single larger perforator. Similarly, if three smaller perforators with equal radii are used instead of a single larger perforator, the resistances between these two systems of perforators will be equal when the smaller radii are (the fourth root of 1/3) times the radius of the single perforator, or 0.76 times the radius of the single perforator. In general, if  $n$  perforators of equal but smaller radii than a single larger perforator are used, the resistances of the two systems will be equal when the radii of the smaller perforators are the fourth root of  $1/n$  times the radius of  $r_1$ .

The above scenarios lead to the next logical question. Suppose one has incorporated the largest diameter vessel in the design of the perforator flap. During the dissection of the flap, the surgeon encounters a second perforator which is smaller in diameter than the first perforator, but can be dissected and included in the flap. Clearly, based on Eq. (2), adding this perforator will reduce the total resistance of the

perforator system. Combining Eqs. (1), (2) and (3), the relationship describing this scenario is as follows:

$R_2 = R_1[1/(1 + x^4)]$  where  $R_2$  is the resistance of the perforator system when a second perforator of radius  $xr_1$  is added to the single perforator of radius  $r_1$  with resistance  $R_1$ . Similarly, if two additional perforators with radii of  $xr_1$  and  $yr_1$  are added to the single perforator, the resistance of the system of three perforators  $R_3$  would be expressed as follows:

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

Based on the above equation, adding a second perforator with a diameter of 0.9 times the single larger perforator will decrease the resistance to approximately 0.6 times the resistance of the single large perforator. However, if adding a second perforator with a diameter of 0.5 times the single larger perforator, the resulting decrease in resistance will only be approximately one-tenth, or 0.9 times the resistance of the single larger perforator.

## Discussion

Several factors influence which perforators and the number of perforators to include when performing a perforator flap. These include the location of the perforator (central vs peripheral, medial row vs lateral), the amount of muscle and fascial trauma involved in including additional perforators, the size of the perforators, the course of the perforators, and the amount of tissue to be used for the reconstruction (i.e. inclusion of Zone 4). In this paper, we attempt to isolate the contribution of size of the perforator vessels to the overall perfusion of the perforator flap, acknowledging that the decision of which perforators to include is a multifactorial undertaking.

The contribution of the length of the perforator vessels to resistance is not considered in our analysis. The length to resistance relationship is a linear one, whereas the radius is inversely related by a power of 4 to resistance. Therefore, the contribution of the radius is much larger than the length. We acknowledge that many of the problems with blood supply in the DIEP flap are related to flow through the venous system.<sup>7</sup> However, the same rules which govern flow through the arterial system also apply to the venous system and, therefore, many of the derivations presented here apply to the venous system. Since flow is directly proportional to pressure, and the venous side is a low pressure system, then changes in length and radius become even more significant. A single veins' radius and length draining a flap along with the low driving pressure limit the drainage of the flap and ultimately the perfusion of the flap. This may explain why in certain fasciocutaneous flaps as well in the DIEP flap, veins appear more numerous and of larger calibre than the arteries. This accommodates for the decreased venous pressure and allows for venous drainage. The contribution of parallel resistance (vena comitante) and the superficial venous system both add to the complexity of the model. We believe that the superficial system drains this flap if and when the superficial system vessels (and specifically the vein) are larger than the perforators found during dissection of the flap. In this case, if the

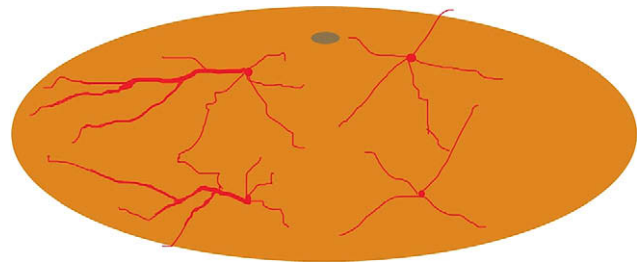
flap is based on the smaller perforating vessels, drainage is forced through the smaller calibre perforators into the deep system and this theoretically hinders flap drainage. The theoretical model above would suggest that a single superficial inferior epigastric vein would have better drainage than the deep system which has two veins in parallel (venae comitantes), if the superficial vein was of larger calibre than perforator venae comitantes (specifically, the perforator venae comitantes were less than 0.84 times the radius of the superficial vein). Interestingly, the radial forearm flap is perfused by the deep system perforators but routinely drained by the superficial cephalic system, as the superficial cephalic system is often of much larger calibre.

Several authors have advocated using the single largest perforator to base the flap upon.<sup>2,4</sup> Based on our mathematical model, any attempt to minimise resistance to flow must include the single largest perforator if possible. Incorporating additional perforators will further reduce the total resistance and increase flow. However, as demonstrated above, the magnitude of reduction in resistance is related to the size of the additional perforator, and the added benefit may not be worth the additional trauma required to include the perforator. We acknowledge that the axial pattern of flow is from medial to lateral. Our interpretation is that larger calibre vessels travel from medial to lateral and that side branches (that travel superior and inferior) and medial branches (that cross the midline) are random and often of smaller calibre. In the situation of a large superior lateral perforator, this may not be enough to supply good perfusion to the inferior medial ipsilateral portion of the flap and, in a case such as this, it may be necessary to include an inferior perforator (Figure 4). This would suggest that the length of the vessel determines the length of the flap, while the width of the flap is influenced more so by supply from adjacent angiosomes. Use of the tissue oximeter allows temporary clamping of this additional perforator so that the decision can be made to include or exclude it.

Another interesting dilemma occurs when the surgeon is faced, for anatomic reasons of dissection, with either using a single large perforator, or using multiple smaller perforators. Based upon our model, the only advantage in using the multiple smaller perforators occurs when these vessels are approximately 0.84 or more times the radius of the single larger vessel (in the case when there are two smaller perforators) or 0.76 or more times the radius of the single larger vessel (in the case when there are three smaller perforators).

Perforators that perforate the muscle at the tendonous inscriptions are also preferred.<sup>4</sup> The success of the flaps based on these vessels has been attributed to their large calibre and short length. These vessels are often the single largest perforators and, based on our model, support the use of these vessels to minimise resistance to flow.

The lateral branch of the deep inferior epigastric artery is the dominant branch in approximately 50% of cases.<sup>4</sup> Therefore, in most cases, perforators off the lateral branch are larger perforators, and attempts should be made to include these large perforators, particularly in cases in which only Hartrampf zones I and III are to be carried by the perforating vessels. Again, one needs to keep in mind that the decision to



**Figure 4** The length of the perforator determines the length of the flap while supply from neighbouring angiosomes determines the width of the flap. In this model, including additional perforators superior to or inferior to the primary perforator should theoretically increase the flap width.

use medial versus lateral row perforators is a multifactorial decision. For instance, if tissue across the midline (Hartrampf zone II) is needed for adequate volume, then a medial row perforator may be a better option, even if it is somewhat smaller than a lateral row perforator.

The idea that 'more is better' is not always the case with regards to the number of perforators on which to base a perforator flap. In fact, data exist which directly correlates the number of perforators used to the rate of complication and fat necrosis.<sup>8</sup> In the discussion of these findings, the authors suggest that in cases where four or five perforators are used, the flap is based on small-diameter vessels. Again, our theoretical model supports these clinical findings.

In conclusion, the technical considerations in planning a DIEP flap are multiple, and one of the goals of the flap design should be to optimise perfusion to the flap. We developed a theoretical model to explain several of the findings observed in clinical practice. We conclude that the best perfused flap involves use of the largest diameter vessel and that, although adding additional perforators will decrease the resistance and increase flow, the magnitude of the benefit depends largely on the calibre of the additional perforator, and this benefit needs to be weighed against the downside of increased muscle and fascial trauma. In addition, using a larger number of perforators instead of a single larger perforator may or may not be beneficial, depending on the relative size of the multiple perforators compared to the larger perforator.

Future projects will include analysis of the venous outflow using a similar theoretical model. In addition, clinical correlation using tissue oxygenation and perfusion in DIEP flaps to confirm this theoretical model are underway.

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**Comment on: Patel SA and 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;61:1316–20**

We read with much interest the article entitled 'A theoretical model describing arterial flow in the DIEP flap related to number and size of perforator vessels' by Patel and Keller. We really appreciate the efforts of the authors in trying to investigate the perfusion factors of perforator flaps. As we already reported,<sup>1–3</sup> supported by the wide experience of several colleagues who internationally have developed this kind of surgical flap, the deep inferior epigastric artery perforator (DIEAP) flap arterial flow is becoming more and more clear. Without any doubts, from a haemodynamic point of view, perforator flaps and particularly the DIEAP flap represent peculiar entities compared to the conventional arterial tree structure of the myocutaneous flaps and the normal circulation.

With the development of perforator flaps, we moved from a multiple musculocutaneous small perforator-based flap with resistances in parallel to a single-conduit perforator-based flap with resistances in series.<sup>1–3</sup> We congratulate the authors for their attempts to clarify the effect of an additional perforator on a larger selected perforator, and for having investigated the differences between a single perforator-based DIEAP flap and a DIEAP flap based on multiple small perforators. This is an interesting point, which we feel to be of great consequence, but clinical evidence is still lacking.

However, it is a common experience that arterial flow does not represent a major problem in the circulation of the DIEAP flap if the harvesting technique is carefully performed. As we recently published,<sup>4</sup> the inversion phenomenon in the arterial inflow and the microcirculation of perforator flaps demonstrate the valid perfusion of perforator flaps.

On the other hand, we feel more efforts must be focused on the venous outflow. Why, in many cases, even in the presence of patent micro-anastomoses, does the DIEAP flap suffer from venous congestion, which may result in partial fat or skin necrosis?<sup>1</sup>

Recently, we studied the relationship between flap weight, and calibre and number of venous conduits that may be considered in optimizing the reliability of the venous drainage of a DIEAP flap. Based on our findings, we developed a structural model that arose from a similar scheme to that used in this article related to the arterial

component, and this is currently in the publishing process.

We are very pleased to note that more studies on the haemodynamics of perforator flaps are currently receiving the attention of the international scientific community. We started almost 5 years ago assessing arterial blood inflow<sup>2,3</sup> and microcirculation<sup>1,4</sup> in perforator flaps. Now, focusing attention on venous drainage, we have completed a systematic investigation of the haemodynamics of the DIEAP flap starting from the arterial section, and passing through the microcirculation to the venous section.

We hope this article together with our studies will stimulate surgeons to consider perforator flaps as new entities not only from an anatomical but also from a haemodynamic point of view.

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Andrea Figus

Department of Plastic and Reconstructive Surgery,  
University of Rome "Sapienza", Italy  
E-mail address: [andreafigus@hotmail.com](mailto:andreafigus@hotmail.com)

Venkat Ramakrishnan

St Andrew's Centre for Plastic Surgery and Burns,  
Broomfield Hospital, Chelmsford, UK

Corrado Rubino

Department of Plastic and Reconstructive Surgery,  
University of Sassari, Sardinia, Italy

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