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ORIGINAL ARTICLE
Reconstructive

In-Vivo Quantitative Mapping of the Perforasomes of Deep Inferior Epigastric Artery Perforators

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Background: There is limited understanding of anatomy of perforator angiosomes, or "perforasomes," of the deep inferior epigastric artery (DIEA). A perforasome is defined as the territory perfused by a single perforator vessel of a named artery, such as the DIEA. Given the clinical significance of this anatomical concept in microsurgical breast reconstruction, this study is a quantitative investigation of DIEA perforasome characteristics and patterns associated with perforasome size, perforator caliber, location and branching, using computed tomographic (CT) angiography.

Methods: Twenty abdominal arterial-phase CT angiograms were analyzed in 3 dimensions using software (Horos). DIEA perforasomes were mapped, yielding data on 40 medial-row and 40 lateral-row perforasomes. Perforator branch extents and number were measured using 3-dimensional multi-planar reconstruction, and perforator caliber on axial slices.

Results: Perforasomes exhibited eccentric branching distributions in horizontal and vertical axes, that is, a majority of perforators were not centrally located within their perforasomes. Lateral-row perforasomes displayed greater horizontal eccentricity than medial-row. There was a positive correlation between perforator caliber and perforasome size. Medial-row perforators had more branches and larger caliber than lateral-row.

Conclusions: This is the first article to quantify relationships between perforators and their territories of supply in vivo, augmenting current understanding of perforasome theory. DIEA perforasomes can be readily visualized and mapped with CT angiography, which may enable effective preoperative flap planning in DIEA perforator flap breast reconstruction. Future investigation may highlight the importance of this information in improving surgical outcomes, including flap survival and fat necrosis reduction, through careful, perforasome-based flap design.
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INTRODUCTION

To date, the literature reflects limited understanding regarding the anatomy of perforator angiosomes, or "perforasomes," of the deep inferior epigastric artery (DIEA). A perforasome is defined as the territory perfused by a single perforator branch of the DIEA (Fig. 1), and this anatomical concept holds increasing clinical significance in the context of autologous breast reconstruction as microsurgical techniques evolve. From the first description of angiosomes as blocks of tissue in 1987 by Taylor and Palmer[1] to the development of the perforator angiosome theory by Saint-Cyr et al.[2] and Rozen et al.,[3] the perforasome concept has gained tangible relevance in vascularized free tissue flap transfers. Several authors, in-

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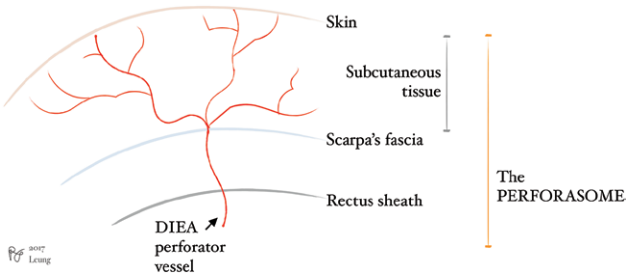

Fig. 1. A diagrammatic representation of a perforasome in an axial slice.

cluding Scheflan and Dinner,[4,5] Hartrampf et al.,[6] and Holm et al.,[7] have explored the perfusion territories of the DIEA through in vivo and cadaveric studies utilizing various imaging techniques, and further, Wong et al.[8] and Rozen et al.[3] have investigated perfusion territories of DIEA perforators in cadaveric flaps. There has, however, not yet been a comprehensive in vivo description of the anatomical features of the DIEA perforasome, which we believe to be of great clinical importance. Given that breast cancer is the most common cancer in women worldwide, with 1.67 million new diagnoses in 2012,[9,10] there has never been a more crucial time to explore improvement of surgical outcomes in deep inferior epigastric artery perforator (DIEP) flap microsurgical breast reconstruction.

This study is an innovative, in vivo, quantitative investigation of anatomical DIEA perforasome characteristics and patterns associated with perforasome size, perforator caliber, location and branching, using CT angiography.

PATIENTS AND METHODS

Twenty consecutive abdominal arterial-phase CT angiograms were retrospectively viewed and analyzed using medical image viewer software, Horos (v. 2.2.0; The Horos Project). The scans were 625 μm fine slices and performed preoperatively to assess DIEA perforators for suitability to DIEP flap breast reconstruction. These angiograms were studied to examine the anatomy of a perforasome.

This study has been conducted with ethics approval (RMH HREC#2006.231) for the analysis of CT angiograms obtained for DIEP flap breast reconstruction.

Data were collected on 80 perforasomes in total. On each scan, 2 DIEA perforasomes per hemi-abdomen were mapped, one "lateral-row" perforasome, and the other, "medial-row." This classification is based on a perforator's location, specifically, the vessel's exit point from the rectus sheath into the subcutaneous tissue, where lateral-row perforasomes arise from perforators, which exit lateral to the longitudinal midpoint of the rectus sheath, and medial-row perforasomes arise from perforators that exit medially. Focus was given to comparing the anatomical differences between these 2 perforasome groups, as clinically, quantification of these distinctions would have the potential to optimize the surgeon's DIEA perforator selection both pre- and intraoperatively, thereby improving postoperative morbidity rates.

Mapping of a perforasome on a CT angiogram was performed by the first author in a systematic, step-wise manner. First, the perforator vessel's exit point from the rectus sheath was marked on a 3-dimensional (3D) multi-planar reconstruction created from the scan using Horos, and its position relative to the umbilicus was recorded. Next, primary and secondary branches of the perforator were followed through slices and marked in all planes, yielding a visualization of the perforasome by demonstrating the distribution of perforator branching, and hence indicating the areas perfused by the perforator and its branches, that is, the perforator angiosome (Fig. 2). Once this mapping

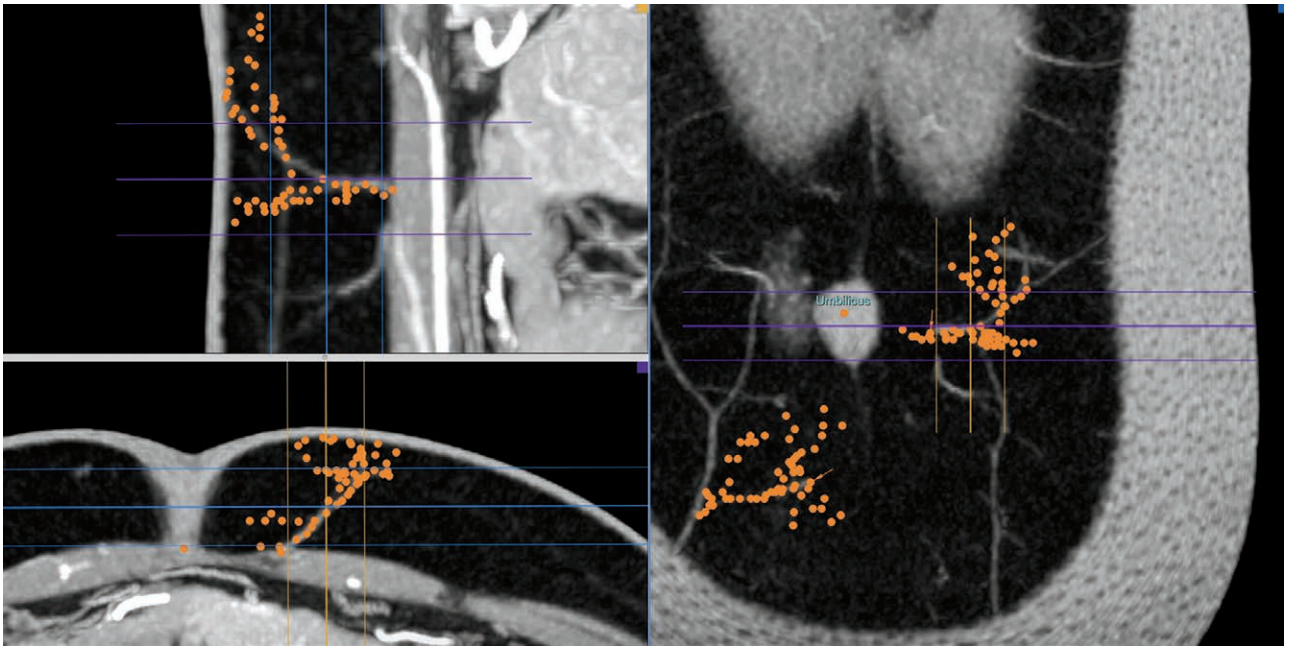

Fig. 2. Mapping of perforasomes using 3D multi-planar reconstruction in Horos.

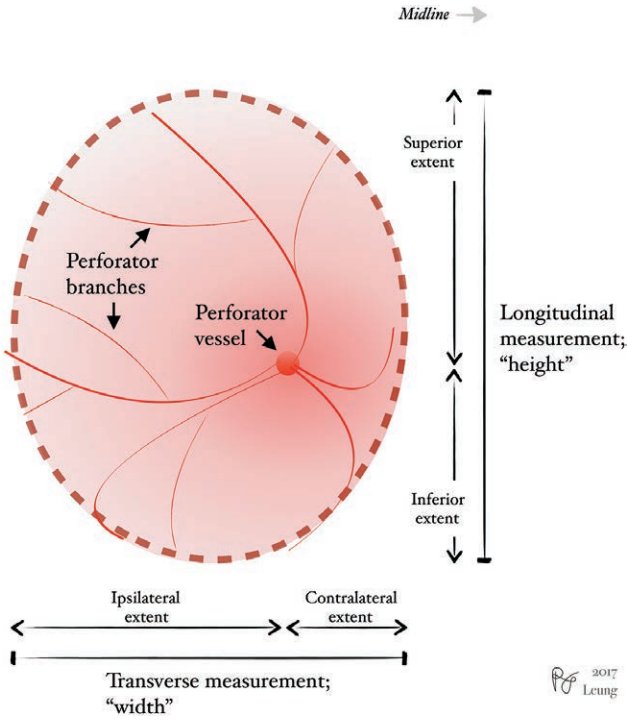

Fig. 3. Illustration of "height" and "width" measurements of a perforasome.

was complete, the distance between the perforator exit point and the ipsilateral-most extent was measured in a transverse plane (mm), then repeated for the contralateral-most extent. The sum of these 2 values was labeled the "width" of the perforasome. Superior-most and inferior-most extents were measured in a longitudinal plane, and the sum of these 2 values was labeled the "height" of the perforasome (Fig. 3).

The perforator vessel lumen diameter, at the level of its exit from the rectus sheath, and number of primary perforator branches was also recorded. In addition, the nature and caliber of inter-perforator vessels were examined. A maximum intensity projection reconstruction was used when required, to facilitate accurate tracing of vessel path throughout this process. All measurements were in millimeters.

This method of mapping was performed for the largest caliber lateral and medial perforators in each hemi-abdomen, that is, the dominant perforators. Only subumbilical perforators were considered, as these are most clinically relevant in DIEP flap breast reconstruction.

Once these data were synthesized from the 20 angiograms and collated, statistical analysis was performed, utilizing software, Stata (v. 15; StataCorp LLC). Data were first checked for normal distribution using the Shapiro-Wilk test. Those with normal distributions were described using mean ± SD, and different groups compared using parametric tests such as *t* test or paired *t* test, χ^2-test or analysis of variance (ANOVA). In the case of ANOVA, the Holm-Sidak method was used for post hoc tests in the event of a statistically significant difference in means detected by the ANOVA. Those that failed the Shapiro-Wilk test for normality were described by their median and range (25%, 75%) and different groups compared using Kruskal-Wallis test.

Perforasome eccentricity and size, plus perforator branching and caliber were examined comparing medial-row and lateral-row populations. Relationships between perforasome height, width, or perforator caliber were examined using linear regression analysis. In addition, power analyses were undertaken, which indicated that in all cases, the sample size was adequate to support the findings (power of performed test when alpha = 0.05: ≥ 0.8).

RESULTS

Our study yielded several relevant findings. The eccentricity, size, perforator caliber, and branching of medial-row and lateral-row perforasome populations were compared and relationships between perforator caliber and either perforasome height or width were examined using linear regression analysis (Table 1).

Perforasome Eccentricity

Perforasome eccentricity was assessed by examining each perforator's location within its perforasome. If the perforasome's ipsilateral and contralateral extents differed by 3 mm or less, the perforasome was categorized as "horizontally concentric." If the ipsilateral extent and contralateral extent differed by greater than 3 mm, that perforasome was categorized as "horizontally eccentric." Overall, only 3 of 80 (3.75%) perforasomes were horizontally concentric. Examining all 80 perforasomes, the mean ipsilateral extent was found to be statistically significantly larger than the mean contralateral extent (mean ± SD by paired *t* test: 39.38 ± 17.43 versus 5.64 ± 11.58, P < 0.001), demonstrating a strong tendency for perforasomes to be ipsilaterally eccentric in this axis. When comparing the degree of horizontal eccentricity of perforasomes between the medial-row population and the lateral-row, medial-row

Table 1. Comparison between Medial-row and Lateral-row Perforasome and Perforator Characteristics

Perforator Dimension	Medial-row (mm)	Lateral-row (mm)	*P*
Horizontal eccentricity, mean ± SD	27.2 ± 22.1	42.34 ± 16.96	< 0.001
Vertical eccentricity, median (range: minimum–maximum)	17.2 (7.2–31.8)	16.2 (7.0–23.8)	NS
Perforasome width, median (range, minimum–maximum)	34.1 (20.4–111.3)	43.5 (20.2–114.4)	NS
Perforasome height, median (range, minimum–maximum)	31.7 (11.8–107.5)	26.1 (8.2–66.9)	NS
Perforator caliber, mean ± SD	1.2 ± 0.3	1.0 ± 0.28	< 0.001
Perforator branch number, median (range, minimum–maximum)	3 (2–4)	2 (2–4)	0.001

NS, did not reach statistical significance.

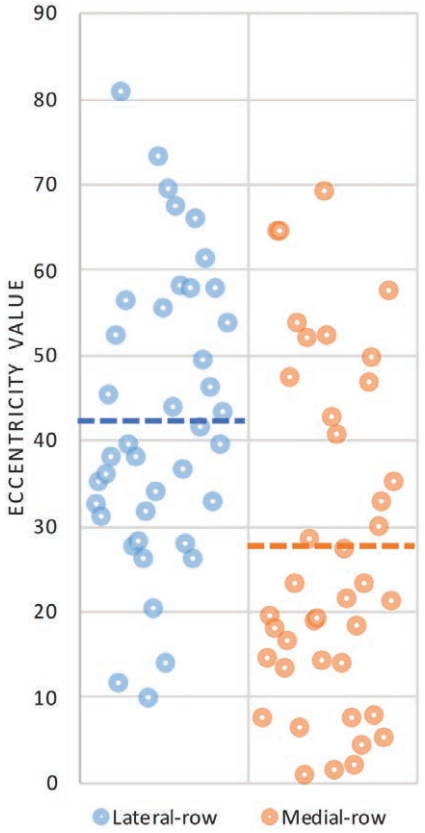

Fig. 4. The horizontal "eccentricity value" is the difference between the ipsilateral and contralateral extent; the larger the value, the more horizontally eccentric a perforasome is. Mean horizontal eccentricity values are represented by the dotted lines.

perforasomes were found to be less horizontally eccentric than lateral-row (Fig. 4), and this was statistically significant ($P < 0.001$). Further, the 3 horizontally concentric perforasomes were all medial-row perforasomes.

With regard to vertical eccentricity, adopting the same definitions as in the horizontal axis, perforasomes were classified as "vertically concentric" when the superior extent and inferior extent differed by less than or equal to 3 mm. Four medial-row and 4 lateral-row perforasomes were found to be vertically concentric. Again, examining all 80 perforasomes, the mean inferior extent exceeded the mean superior extent ($P = 0.002$), proving the inferior eccentricity of perforasomes in the vertical axis also. However, when comparing medial-row and lateral-row populations, there was no statistically significant difference in degree of eccentricity in this axis.

Perforasome Size

Perforasome size was reflected in 2 measurements, the "height" and "width" of the perforasome. These values were determined as described in the methods. The average perforasome, without distinguishing between medial- or lateral-row, had a width of 45.0 mm and height of 33.8 mm. When comparing medial- and lateral-row perforasomes, the former had a slightly greater median height but a lesser median width than the latter, though these differences did not reach statistical significance. Using these values and the formula

$$(area)_{perforasome} = \frac{average\ height(cm)}{2} \times \frac{average\ width(cm)}{2} \times \pi$$

to estimate the average perforasome area, the average medial-row perforasome was found to be 124.3 cm^2, and the average lateral-row, 113.1 cm^2.

Perforator Caliber

Perforator vessel caliber was measured by lumen diameter on angiogram. Mean perforator diameter for medial-row perforators, 1.239 mm, was significantly larger than that of lateral-row perforators, 0.967 mm ($P \leq 0.001$).

Perforasome Size and Perforator Caliber

Using linear regression, there was a statistically significant positive correlation between perforator caliber and perforasome size, both in width and height of the perforasome, that is, the larger the source perforator vessel caliber, the larger the corresponding perforasome.

The regression model fit for perforasome width and perforator diameter was found to be significant ($P = 0.0008$), as was the correlation between perforasome height and diameter, with t-value = 3.48 ($P = 0.001$). The regression model fit for perforasome height and perforator diameter was also significant ($P = 0.0001$), as was the correlation between perforasome height and diameter, with t-value = 4.08 ($P = 0.000$).

Number of Primary Branches

The median number of primary branches was statistically significantly greater in the medial-row perforator group compared with lateral-row. First-tier branching, more often than not, was noted to occur at the level of Scarpa's fascia.

Interperforator Zone

Although linking vessels between perforasomes are an already-established concept in the literature,[2,11–13] we chose to include the examination of these anastomoses in our results as their relevance to the harvest of large flaps is crucial. Of the 2 classes of inter-perforator vessel, true and choke anastomoses, both were seen in our study. They are also known, respectively, as direct and indirect linking vessels.[2] On CT angiogram, these vessels could be visualized, and their caliber could be measured, enabling the distinction between true and choke anastomoses to be made (Fig. 5).

DISCUSSION

Due to the incongruence in perforasome nomenclature in the literature, where confusion exists when distinguishing between a perforasome and the territory which has the potential to be supplied by a perforator, we first aim to clarify terms used in this article and propose the standardization of definitions. The commonly accepted definition of a perforasome is the territory supplied by a single perforator and its branches, the delineation or

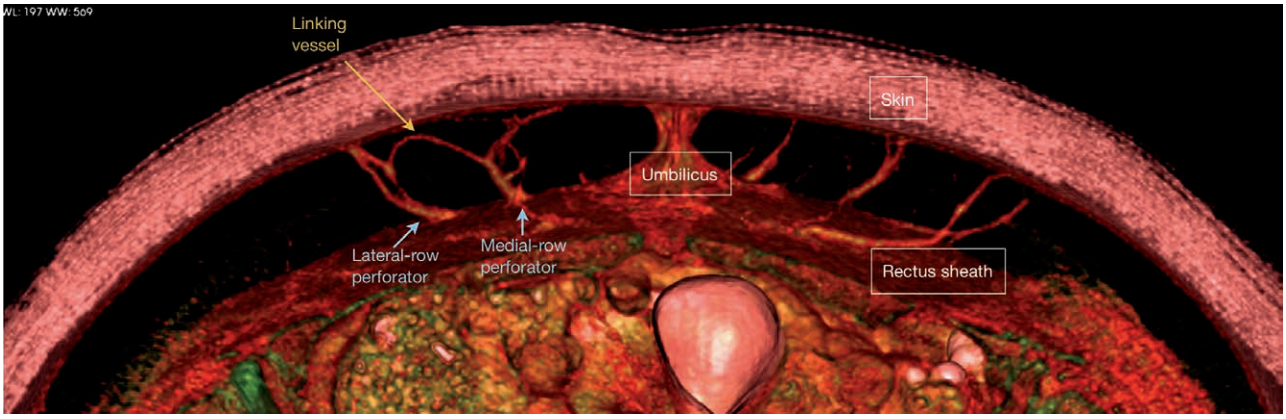

Fig. 5. 3D volume-rendered reconstruction of an axial abdominal CT angiogram. Note the linking vessel (orange arrow) between the lateral-row and medial-row perforators. Its caliber in comparison with that of the branches it joins indicates that it is a true anastomosis.

"border" being at the linking vessels. In the context of flap harvest and subsequent perforator hyper-perfusion, the resultant dilatation and hyperplasia[11] of linking vessels is such that adjacent perforasomes gain the potential to be perfused by the perforator on which the flap has been raised, leading to an altered and larger perfusion territory of the source perforator. Therefore, the relevant terms, based on and adapted from 2 articles published by Taylor et al.,[11,12] are defined as follows:

1. The anatomical territory of a perforator, or an anatomical perforasome, is defined by a line drawn through the anastomotic zone and correlates with the traditionally accepted definition of the perforasome, as mentioned in the paragraph above.
2. The clinical or functional territory of a perforator encompasses the anatomical territory plus the adjacent, linked, perforasomes also perfused by this single perforator. This may be called the functional perforasome.

This study focuses on the anatomical perforasome. What is the clinical relevance of this in DIEP flap breast reconstruction? The functional perforasome of a DIEP flap is based, intrinsically, on the characteristics of the anatomical perforasome. In fact, we ought to consider anatomical perforasomes to be the "units," which together, form a functional perforasome.

Our research into the use of CT angiography to map anatomical perforasomes may therefore enable the visualization of functional perforasomes. This may be achieved by mapping the anatomical perforasome of a selected perforator, examining the caliber of surrounding inter-perforator vessels, and predicting which adjacent anatomical perforasome "units" will also be perfused by this source vessel. Taylor et al.[11] describe that units directly adjacent and connected by choke anastomoses to the source vessel's anatomical perforasome will be perfused by this perforator vessel, but that no further units adjacent to those connected by choke zones can be supported. However, if a unit is linked to the source vessel's anatomical perforasome by a true anastomosis, it, and the next adjacent unit, will be perfused by this perforator vessel. Once the relevant units are mapped, the resulting territory will represent the functional perforasome. This may facilitate the optimization and personalization of preoperative flap design, thereby minimizing postoperative tissue necrosis. In addition, it may provide surgeons with the ability to take eccentricity, size, and shape of a functional perforasome into consideration, rather than just vessel caliber, when selecting a perforator preoperatively.

Further, this article is the first to quantify the typical features of an anatomical DIEA perforasome in vivo. These characteristics are not only of value in their augmentation of current perforasome understanding but also play a role in revealing and supporting reasoning behind why fat necrosis and flap loss occur. Although the eccentricity of perforasomes has been mentioned in literature,[3,8] our article's definitive quantification of this in anatomical perforasomes highlights that the location of a perforator in relation to both its anatomical and functional territory is variable and likely not central at all, which may explain the unpredictable occurrence of fat and skin necrosis in flap tissue that was selected based solely on its proximity to the source perforator. Moreover, this study has substantiated the relationship between perforator caliber and perforasome size, which clinically, will allow more certainty in perforator selection and its impact on flap design.

The demonstration of these anatomical DIEA perforasome features with CT angiography in vivo, compared with cadaveric studies of DIEA perforator territory, holds more relevance to preoperative imaging and tailoring of flap design, especially as it occurs within natural physiological conditions. Schaverien et al.[14] also confirms that perfusion territory is underestimated in cadaveric studies, likely resulting from collapse of precapillary smooth muscle sphincter cells. Though there is some potential for in vivo underestimation due to vasoconstriction and image resolution, theoretically, this should be to a much lesser degree than that displayed in cadaveric imaging. The authors therefore believe the in vivo investigation of anatomical perforasome characteristics to be highly relevant in increasing understanding and improving surgical outcomes through careful flap planning, especially in the

setting of development of preoperative perforasome mapping techniques.

It must be noted that preoperative imaging of DIEA perforasomes yields a different representation of perforator territory when compared with that of flap imaging, cadaveric, or otherwise. This is simply because a perforator's functional angiosome before flap harvest exists only as a theoretical concept or estimation. Contrastingly, when raising a DIEP flap, ligation of all perforators except the selected source vessel results in the actualization of the functional perforasome. Even then, this is not the true functional perforasome, as vessel hyperplasia of choke anastomoses will have not yet had time to occur.[11] Flap imaging also allows the dynamic imaging of flow within the functional perforasome. A limitation of our in vivo use of CT angiography is its static nature; however, flow through the inter-perforator zone over time is a less relevant variable in preoperative imaging when only estimation of functional perforasome extent can occur.

In future, clinical correlation studies are warranted to explore the effect of preoperative mapping on flap survival rates in practice. Further anatomical and clinical research into inter-perforator zones may identify image analysis techniques, which can optimize accuracy of functional perforasome estimates when mapping with CT angiography.

Finally, to address the findings of our study in comparison with the literature on perforasomes, our results are largely in concordance with and support the results of current publications. One point to note was the reports by Wong et al.[8] and Rozen et al.[3] of midline cross by medial-row perforator branches, which was not seen in our study. This is a result of our strict definition of the anatomical perforasome, meaning that only branches within the limits of the surrounding anastomotic junctions were considered to belong to the perforasome in question. As per Moon and Taylor[15] and our observations in this study, midline crossing occurs almost exclusively by way of choke anastomoses located across the midline, meaning that an anatomical perforasome will very rarely extend beyond the midline boundary. Another consideration is the study by Wong et al.[8] of DIEA perforasomes and their quantification of perforasome area. The article describes use of flap imaging to quantify the functional perforasome, and consequently, their figures cannot be directly compared with our quantification of the anatomical perforasome.

CONCLUSIONS

This is the first article to demonstrate quantitative relationships between DIEA perforator vessels and their anatomical territories of supply in vivo. This new data serve to augment current understanding of perforasome theory and may aid surgical planning. Anatomical DIEA perforasomes can be readily visualized and mapped with CT angiography, which has the potential to enable effective preoperative flap planning in DIEP flap breast reconstruction. Future investigation may highlight the importance of this information in improving surgical outcomes, including flap survival and fat necrosis reduction, through careful, perforasome-based flap design.

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