

Vascular coverage of the anterior knee region – an anatomical study

Lena Hirtler,¹  Anke Lübbers² and Claus Rath¹

¹Division of Anatomy, Center for Anatomy and Cell Biology, Medical University of Vienna, Vienna, Austria

²Department of Surgery, Malteser Hospital St Franziskus-Hospital, Flensburg, Germany

Abstract

Descriptions of vessel angiosomes or perforasomes throughout the human body are quite frequent, and led to the development of flaps nowadays commonly used to surgically cover skin and soft tissue defects. In these procedures, the surgeon requires a profound anatomical knowledge of the respective blood vessels and the extent of the perfused area to define the size of the graft. In the region of the knee joint, descriptions of flaps based on the superior lateral genicular artery and descending genicular artery are quite frequent. In contrast, information regarding other popliteal branches is scarce or non-existent. The aim of this study was to provide a concise and complete overview on the extent and variability of the perforator angiosomes of the femoral and popliteal arteries in the anterior knee region. Twenty lower extremities were dissected, the respective perforators identified and perfused with dye. All resulting angiosomes were marked and documented. A total of 84 angiosomes were identified in all specimens, with an average of 4.2 (3–6) angiosomes per specimen. The average size of the angiosomes was $97.04 \pm 72.30 \text{ cm}^2$ (8.61–360.41 cm^2), their source vessels had an average diameter of $1.42 \pm 0.54 \text{ mm}$ (0.60–3.25 mm). The complex and highly variable distribution of perforator angiosomes of the anterior knee region and especially of its less frequently investigated distal part was demonstrated. Based on these results, the planning of existing perforator flaps in this region and the development of flaps including the inferior medial or inferior lateral genicular arteries may be facilitated.

Key words: anterior knee region; descending genicular artery; inferior lateral genicular artery; inferior medial genicular artery; perforator angiosomes; superior lateral genicular artery; superior medial genicular artery.

Introduction

The need to cover skin and soft tissue defects in reconstructive surgery is omnipresent, requiring a profound knowledge not only of the different layers throughout the body but especially of their supplying blood vessels and nerves. In the 19th century, surgeons started evaluating the respective vascularization of the skin. One of the first anatomical descriptions of skin perfusion was by Carl Manchot in 1889 (Manchot, 1889), illustrating large areas based on the perfusion of all main vessels throughout the human body (Fig. 1a). In 1936, Salmon (1936) was able to put more detail in those vascular territories by the use of radiography

(Fig. 1b). Based on the supplying vessels and the concept of angiosomes, specific vascular territories were defined throughout the body (Fig. 1c) by Taylor and Palmer (1987), leading to a multitude of flaps described in the literature.

For further differentiation of cutaneous flaps from fasciocutaneous flaps, Koshima and Soeda (1989) introduced the term ‘perforator flaps’ in 1989 (Blondeel et al. 2003). Those perforator flaps were based on perforating vessels defined by their origin from one of the axial vessels of the body and coursing through several other layers towards the subcutaneous fat layer (Blondeel et al. 2003).

Skin perfusion in the knee joint region is mostly performed by arteries of the joint’s articular network (Fig. 2). These arteries are comprised of the descending branch of the lateral femoral circumflex artery originating from the deep artery of the thigh, the descending genicular artery (DGA) of the femoral artery, the superior lateral (SLGA) and medial (SMGA) genicular arteries, the inferior lateral (ILGA) and medial (IMGA) genicular arteries of the popliteal artery, as well as the anterior (ATRA) and posterior (PTRA) recurrent arteries of the anterior tibial artery (Kirschner et al. 1998). Those arteries not only provide

Correspondence

Lena Hirtler, Division of Anatomy, Center for Anatomy and Cell Biology, Medical University of Vienna, Währinger Straße 13, 1090 Vienna, Austria. E: lena.hirtler@meduniwien.ac.at

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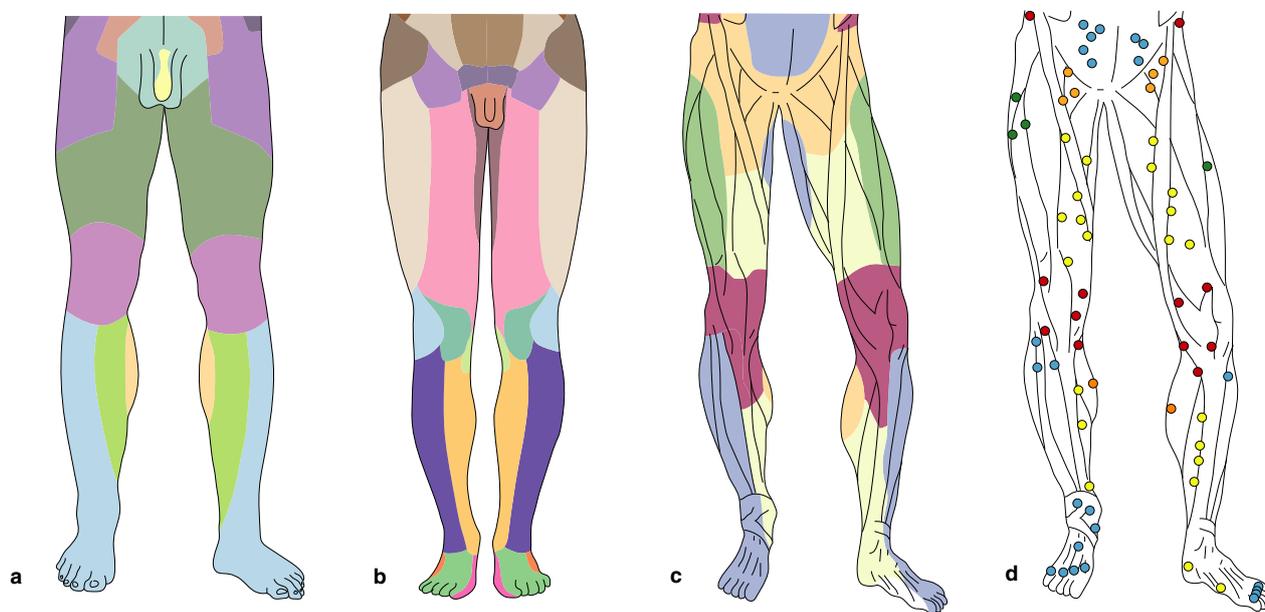


Fig. 1 Synopsis of the development of the angiosome concept. (a) Early concept of Manchot (1889), (b) angiosomes based on radiographic evaluation by Salmon (1936), (c and d) Perforators (c) and their angiosomes (d) as depicted by Taylor and Palmer (1987).

nutrition to the soft tissue around the knee, but are also responsible for the vascularization of the osseous structures. The lateral femoral condyle is supplied via anastomoses between the SLGA and the ILGA, the medial femoral condyle mainly via the DGA and the SMGA. The IMGGA supplies the medial proximal tibia without any anastomoses to vessels supplying the medial femoral condyle, and the ILGA is responsible for the lateral tibial condyle (Kirschner et al. 1998; Reddy & Frederick, 1998; Taylor & Pan, 1998; Hugon et al. 2010; Yamamoto et al. 2010; Sananpanich et al. 2013).

These branches of the articular network of the knee are already widely used for reconstructive procedures: (i) as cutaneous flaps with the SLGA as source vessel (Laitung, 1989; Hayashi & Maruyama, 1990a; Spokevicius & Jankauskas, 1995; Taniguchi et al. 2009); (ii) as pure corticoperiosteal flaps (Hertel & Masquelet, 1989) or with additional skin flaps. In these procedures, the source vessel is either the DGA (Guan et al. 1985; Martin et al. 1991; Sakai et al. 1991; Kobayashi et al. 1994; Doi et al. 2000; Muramatsu et al. 2003; Fuchs et al. 2005; Bakri et al. 2008; Cavadas & Landin, 2008; Gaggl et al. 2008; Jones et al. 2008, 2010; Kalicke et al. 2008; Doi & Hattori, 2009; Dubois et al. 2010; Pelzer et al. 2010; Kakar et al. 2011; Rahmanian-Schwarz et al. 2011; Iorio et al. 2012; Higgins & Burger, 2014; Kazmers et al. 2017; Tremp et al. 2017) or the SLGA (Higgins & Burger, 2014; Wong et al. 2015; Morsy et al. 2018).

The existing literature of course represents the current focus of surgical procedures. This leads to quite frequent descriptions of the DGA and the SLGA, as shown in the previous paragraph, whereas only few data are available

concerning the ILGA and the IMGGA as those arteries are not used as source vessels for perforator flaps yet (Hertel & Masquelet, 1989; Kirschner et al. 1998; Taylor & Pan, 1998; Pan & Taylor, 2009).

However, looking at the information on the perforator angiosomes of the DGA, the focus most often lies on its saphenous branch and not on the different direct branches of the DGA itself. Additionally, the different branching patterns of the DGA and the origin of its saphenous branch with the resulting variances of the different angiosome patterns are mostly left unmentioned (Acland et al. 1981; Hertel & Masquelet, 1989; Hayashi & Maruyama, 1990b; Ballmer & Masquelet, 1998; Kirschner et al. 1998; Iorio et al. 2012; Zheng et al. 2015; Parvizi et al. 2016). A similar challenge arises when looking at information of the SLGA. Information on the morphology of the artery may be frequently found (Walton & Bunkis, 1984; Hayashi & Maruyama, 1990b; Kirschner et al. 1998; Wong et al. 2015; Morsy et al. 2018). Also the supplied profound structures and the location of the respective skin areas were described (Laitung, 1989; Hayashi & Maruyama, 1990b; Zhang, 1990; Pan et al. 2004; Fathi et al. 2008; Pan & Taylor, 2009; Nguyen et al. 2011; Boonrod et al. 2016; Parvizi et al. 2016; Morsy et al. 2018), but data on the respective size of the perforator angiosomes are hitherto lacking.

The aim of this study was therefore to evaluate the skin perfusion of the respective areas of the arteries of the femoral artery and the popliteal artery supplying the articular network of the knee joint. Besides presenting a complete overview on the perforator angiosomes of the

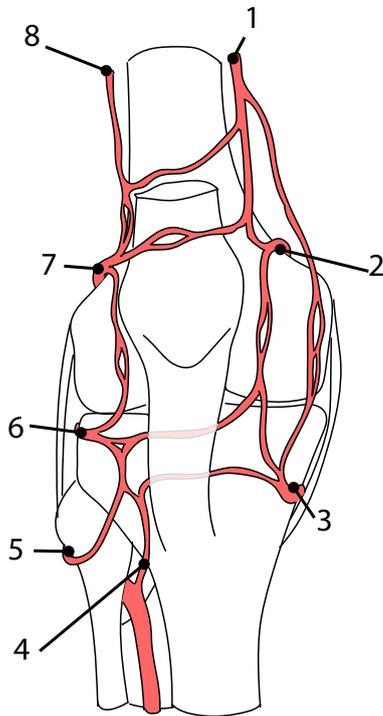


Fig. 2 Overview of the arterial network around the knee joint. Descending genicular artery (DGA) (1), descending branch of the lateral circumflex femoral artery (8), superior lateral (SLGA) (7) and medial (SMGA) genicular arteries (2), inferior lateral (ILGA) (6) and medial (IMGA) genicular arteries (3), anterior (ATRA) (4) and posterior (PTRA) (5) recurrent arteries of the anterior tibial artery.

anterior knee region, this study will provide information on hitherto neglected arteries of this area to expand the morphological knowledge and facilitate new surgical procedures in this area.

Materials and methods

Twenty fresh-frozen lower extremities (10 left, 10 right) originating from a total of 20 voluntary body donations to the Center of Anatomy and Cell Biology of the Medical University of Vienna were obtained. The project was approved by the institutional review board (1588/2013). Specimens were included if they showed no signs of previous surgical interventions, no signs of severe arteriosclerosis or reports and signs of nerve damage and sufficient tissue quality.

Dissection

The leg axis, the patella and the tibial tuberosity were marked on the skin. After identification of the femoral artery, meticulous dissection of its branches was performed using a surgical microscope. All branches distal to and including the DGA were marked for injection until the bifurcation of the popliteal artery into the anterior and posterior tibial arteries.

A tear duct cannula was inserted into each vessel, and different colored solutions (methylene blue and lake pigments in green and

red) were injected to dye the appendant perforator angiosome. The outlines of the angiosomes were marked and recorded photographically in a standardized fashion (Fig. 3). To minimize color effusion bias, each angiosome was marked immediately after color injection and sufficient staining of the angiosome. The amount of color effusion may also be seen in Fig. 3, as the skin coloration in the final photographic overview does not match the marked angiosome. Additionally, each supplying vessel was marked and recorded photographically to document their respective position.

After completion of the dissection, all marked angiosomes were copied onto tracing paper to facilitate further measurements without distortion.

Evaluation

Based on the axis of the leg and the knee joint line, a coordinate system was created using the midpoint of the patella as its center. In each angiosome, maximum width and length, and the distance of its center to the longitudinal and transversal axes of the coordinate system were measured. The diameter of each supplying vessel was measured with a sliding caliper (accuracy 0.01 mm) at its origin from the respective source vessel (femoral or popliteal arteries).

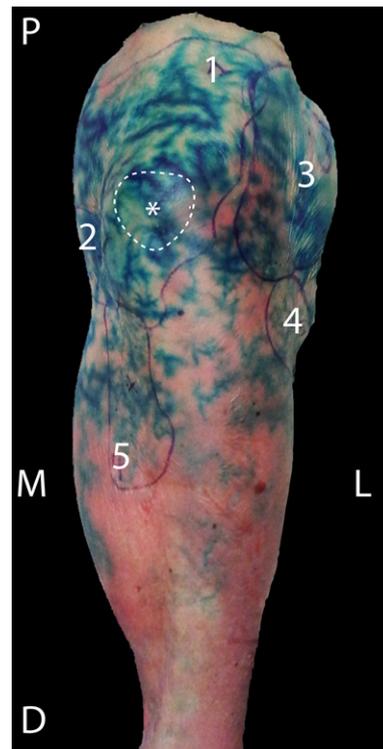


Fig. 3 Example of successful skin coloration of a left specimen during dissection. The angiosomes of the descending genicular artery (DGA) (1), its saphenous branch (2), the superior lateral genicular artery (SLGA) (3), the inferior lateral genicular artery (ILGA) (4) and the inferior medial genicular artery (IMGA) (5) are shown. Asterisk is positioned at the center of the patella. M = medial, L = lateral, P = proximal, D = distal. Note the difference between skin coloration and marked angiosome due to color effusion.

All angiosomes were digitized and evaluated using ImageJ® (<https://imagej.nih.gov/ij/>). The areas were vectorized with Adobe Illustrator® (Adobe Systems) and inserted into a standardized coordinate system for optimal visualization.

Statistics

For all metric data mean, standard deviation and range were documented. Normal distribution of data was evaluated by visualization in boxplots and by the Shapiro–Wilk test. Differences were assessed using the Student's *t*-test. For the correlation between vessel diameter and size of the corresponding perforator angiosome, a Spearman rho test (IBM® SPSS® Statistics 23) was performed as data were not distributed normally. The correlation coefficient was interpreted as follows: ± 0.7 –1 strong, ± 0.5 –0.7 moderate, ± 0.3 –0.5 low, $< \pm 0.3$ weak correlation. A *P*-value < 0.05 was considered as statistically significant.

Results

A total of 84 angiosomes were identified in all specimens, with an average of 4.2 (3–6) angiosomes per specimen. The average size of the angiosomes was $97.04 \pm 72.30 \text{ cm}^2$ (8.61–360.41 cm^2), and their source vessels had an average diameter of $1.42 \pm 0.54 \text{ mm}$ (0.60–3.25 mm).

The angiosome of the DGA was successfully perfused in all specimens (20/20), the saphenous branch of the DGA originated separately from the femoral artery in 10 specimens (10/20). The angiosome of the SLGA was successfully perfused in 19 of 20 (no skin coloration in 1), the angiosome of the IMGGA in 15 of 20 (no skin coloration in 5), the angiosome of the ILGA in 12 of 20 (no skin coloration in 8), and the SMGA in 1 of 20 (no skin coloration in 19). Table 1 provides a summary of the angiosomes and their respective perforator vessels. The angiosomes were highly variable in shape and size (Fig. 4a). The concise location documentation of all angiosome-centers may be found in Table 2 and Fig. 4b.

The angiosome of the saphenous branch of the DGA was always more posteriorly and distally to the angiosome of the DGA when originating separately from the femoral artery ($P = 0.001$; Fig. 5). The size of the angiosome of the DGA did not differ significantly if the saphenous branch

originated separately from the femoral artery. The cutaneous branches from the muscular and osteoarticular branches combined supplied an average area of $153.45 \pm 81.22 \text{ cm}^2$ (53.90–264.74 cm^2) and the corresponding angiosome of the saphenous branch an average area of $91.55 \pm 63.98 \text{ cm}^2$ (24.55–260.44 cm^2), resulting in a total area of $245.00 \pm 87.61 \text{ cm}^2$ (134.20–379.55 cm^2). This total area was significantly larger than the area supplied by a DGA without a separate femoral origin of the saphenous branch [$162.67 \pm 84.76 \text{ cm}^2$ (55.34–360.41 cm^2), $P = 0.047$].

The Spearman rho test showed a moderate positive correlation between the size of the angiosome and its respective source vessel ($P < 0.001$, $r = 0.604$).

Discussion

The results of this study provide a hitherto lacking detailed overview of the perfusion of the skin of the anterior knee region, and demonstrate the high variability of the perforator angiosomes and their supplying vessels (Fig. 4). The DGA and the SLGA were found most constantly. Apart from the established arteries composing the articular network, additional direct perforators from the femoral artery or popliteal artery were identified. Especially their high variability makes the dependable mapping of these perforators and their respective angiosomes a challenging task (Manchot, 1889; Salmon, 1936; Taylor & Palmer, 1987; Taylor & Pan, 1998).

DGA

The DGA originates from the femoral artery at the level of the adductor hiatus (Acland et al. 1981; Koshima et al. 1988; Martin et al. 1991; Scheibel et al. 2002; Pan & Taylor, 2009; Dubois et al. 2010; Yamamoto et al. 2010; Rahmaman-Schwarz et al. 2011; Gocmen-Mas et al. 2012) and has been described to subdivide itself into three main branches – a saphenous branch, a muscular branch and an osteoarticular branch (Hertel & Masquelet, 1989; Martin et al. 1991; Ballmer & Masquelet, 1998; Scheibel et al. 2002; Dubois et al. 2010; Yamamoto et al. 2010; Gocmen-Mas et al. 2012; Garcia-Pumarino & Franco, 2014). The classification of three

Table 1 Size of the respective perforator angiosomes and the corresponding vessel diameters.

Source vessel	Size of angiosome (cm^2)	Diameter of vessel (mm)
DGA	158.06 ± 80.93 (53.90–360.41)	1.77 ± 0.64 (0.7–3.25)
Saphenous branch	91.55 ± 63.98 (24.55–260.44)	1.24 ± 0.2 (0.7–1.4)
SLGA	107.87 ± 48.42 (18.65–238.43)	1.54 ± 0.52 (0.7–2.7)
SMGA	33.51	1.20
ILGA	48.87 ± 36.43 (8.61–139.50)	1.19 ± 0.41 (0.2–2)
IMGGA	85.93 ± 75.87 (18.98–327.16)	1.32 ± 0.51 (0.65–2.35)

DGA, descending genicular artery; ILGA, inferior lateral genicular artery; IMGGA, inferior medial genicular artery; SLGA, superior lateral genicular artery; SMGA, superior medial genicular artery.

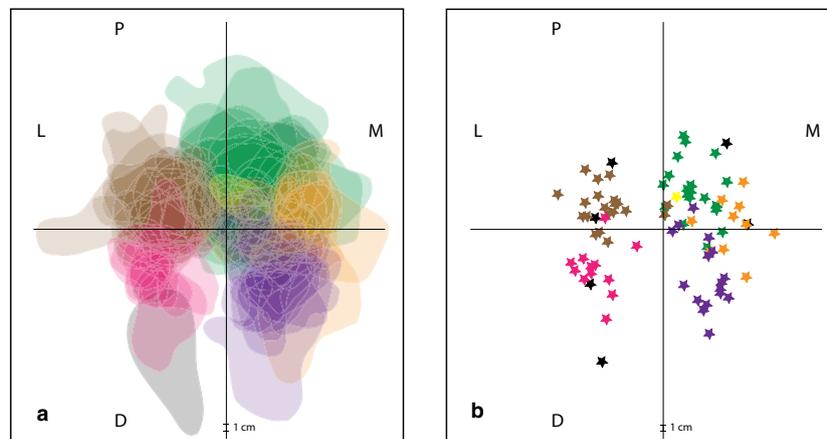


Fig. 4 Overview of the angiosomes of the anterior knee region. Center of the coordinate system is the center of the patella. The x-axis is located parallel to the joint line at the level of the center of the patella, the y-axis follows the longitudinal axis of the leg. M = medial, L = lateral, P = proximal, D = distal. (a) The distribution of the angiosomes. (b) The distribution of the respective centers of the angiosomes. DGA (descending genicular artery; green), its saphenous branch (orange), SLGA (superior lateral genicular artery; brown), SMGA (superior medial genicular artery; yellow), ILGA (inferior lateral genicular artery; pink), IMGGA (inferior medial genicular artery; purple), direct perforators (gray/black).

Table 2 Positions of the centers of the angiosome of each investigated source vessel. Negative values may be interpreted as distal to the joint line or lateral to the longitudinal axis. See also Fig. 4 for visualization.

Source vessel	Position to joint line (cm)		Position to longitudinal axis (cm)	
DGA	Proximal	1.23 ± 4.47 (-1.50 to 14.00)	Medial	4.34 ± 2.65 (0.00 to 8.50)
Saphenous branch	Proximal	1.65 ± 2.86 (-2.00 to 5.00)	Medial	9.50 ± 3.55 (4.00 to 17.00)
SLGA	Proximal	4.48 ± 2.68 (-1.00 to 9.00)	Lateral	-7.34 ± 3.35 (-14.50 to 0.50)
SMGA	Proximal	6.00	Medial	2.00
ILGA	Distal	-4.43 ± 3.96 (-13.00 to 2.50)	Lateral	-9.17 ± 2.09 (-12.00 to 5.00)
IMGGA	Distal	-5.57 ± 5.18 (-15.50 to 3.50)	Medial	5.40 ± 2.00 (1.30 to 8.50)

DGA, descending genicular artery; ILGA, inferior lateral genicular artery; IMGGA, inferior medial genicular artery; SLGA, superior lateral genicular artery; SMGA, superior medial genicular artery.

main types of branching patterns by Dubois et al. (Dubois et al. 2010; Garcia-Pumarino & Franco, 2014; Table 3) does not only show a relative frequency of these patterns, but also explains why the muscular branch and the osteoarticular branch are often described as musculoarticular branch due to their frequent occurrence as common trunk (Acland et al. 1981; Gocmen-Mas et al. 2012). Despite its highly variable branching patterns, the DGA was the most constant artery (20/20).

Apart from blood supply via the osteoarticular branches towards the medial femoral condyle, the DGA supplies the surrounding muscles through its muscular branch, i.e. the sartorius muscle, the gracilis muscle, the rectus femoris muscle, the vastus medius and intermedius muscles. Also, the distal parts of the adductor muscles are partly supplied by it (Martin et al. 1991; Kirschner et al. 1998; Scheibel et al. 2002; Pan & Taylor, 2009; Dubois et al. 2010; Yamamoto et al. 2010; Gocmen-Mas et al. 2012; Garcia-Pumarino & Franco, 2014). Additional anastomoses were described

connecting the DGA with the SLGA (Ballmer & Masquelet, 1998; Pan & Taylor, 2009).

Its cutaneous branch, the saphenous branch, is described joining the course of the saphenous nerve between the sartorius muscle and the tendinous insertion of the gracilis and adductor magnus muscles. Occasionally it may also pass distal to the adductor hiatus (Acland et al. 1981; Hertel & Masquelet, 1989; Martin et al. 1991; Bertelli, 1992b; Ballmer & Masquelet, 1998; Kirschner et al. 1998; Scheibel et al. 2002; Pan & Taylor, 2009; Dubois et al. 2010; Yamamoto et al. 2010; Iorio et al. 2012; Garcia-Pumarino & Franco, 2014). Although the saphenous branch may be absent (Acland et al. 1981), many additional cutaneous perforators of the DGA exist and alternative cutaneous branches may arise directly from the popliteal area to supply the respective skin area. This variable existence of the saphenous branch and the presence of additional cutaneous branches of the muscular or osteoarticular branches of the DGA were also shown by this study. In 10 out of 20 specimens, a separate

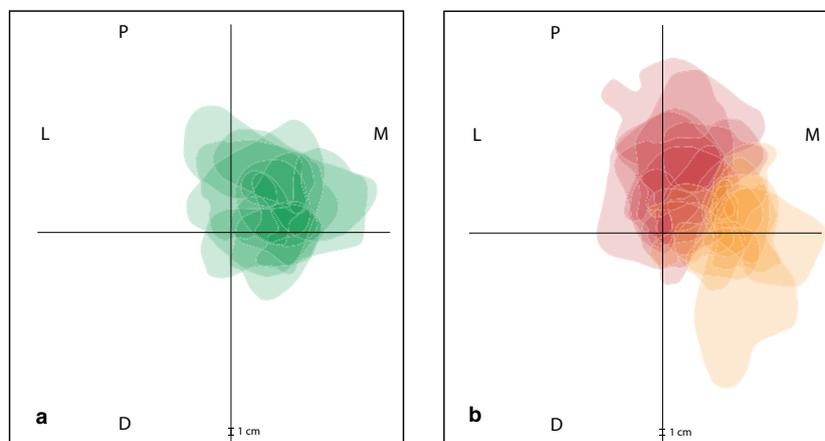


Fig. 5 Angiosome of the descending genicular artery (DGA) in cases of a common trunk including the saphenous branch (a, green), and in cases with a separate origin of the saphenous branch from the femoral or popliteal artery (b; DGA, red; saphenous branch, orange). The center of the coordinate system is the center of the patella. The x-axis is located parallel to the joint line at the level of the center of the patella, the y-axis follows the longitudinal axis of the leg. M = medial, L = lateral, P = proximal, D = distal.

saphenous branch originating from the femoral or popliteal arteries was identified by its course parallel to the saphenous nerve. Also, direct perforators from the femoral and popliteal arteries were found supplying the perigenicular skin in six cases.

Overall, the DGA is described as emerging from the femoral artery at a level of 11.9–17.0 cm above the joint line (Bertelli, 1992a; Ballmer & Masquelet, 1998; Rahmanian-Schwarz et al. 2011; Iorio et al. 2012), or 8.8–12.0 cm above the adductor tubercle (Kirschner et al. 1998; Zheng et al. 2015) with a diameter of 1.5–3.5 mm (Martin et al. 1991; Bertelli, 1992a; Ballmer & Masquelet, 1998; Doi et al. 2000; Dubois et al. 2010; Yamamoto et al. 2010; Rahmanian-Schwarz et al. 2011). An average length of the pedicle of 6.92 cm was reported (Dubois et al. 2010). The described corresponding angiosome measured 70 cm² and was supplied by direct cutaneous branches of the DGA. It was centered over the medial femoral condyle with the perforator, always in direct continuity with the septum between sartorius and vastus medialis muscles (Acland et al. 1981; Iorio et al. 2012; Zheng et al. 2015). In comparison, the angiosome supplied by the DGA through cutaneous branches of the muscular and osteoarticular branches alone – in cases of a separate saphenous branch – measured 153.45 ± 81.22 cm² in this study. This was roughly twice as large as hitherto reported (Iorio et al. 2012). The reason for this large difference in size may be the great variability of angiosomes, shown by the high standard deviation, and the number of specimens used ($n = 12$ and $n = 20$).

Information on the total number of angiosomes supplied by the DGA itself is scarce in literature. Most often, the point of focus is the vascularized cutaneous area of the saphenous branch – without differentiation of its origin. It may emanate from the DGA, or separately from the femoral artery, easily identifiable by its course parallel to the

saphenous nerve. Its origin, apart from subdividing from the DGA, was described at an average of 9.0–19.0 cm above the medial joint-line with a diameter of 1.2 mm (0.7–1.8 mm; Hertel & Masquelet, 1989; Ballmer & Masquelet, 1998). The angiosome of the saphenous branch measured an average area of 361 cm², overlapping the angiosome of the DGA, but going much farther towards posterior and distal (Iorio et al. 2012). Similarly, in this study the position of the angiosome of the DGA differed significantly depending on the existence of the separate saphenous branch ($P = 0.001$; Fig. 5). Here, however, the measured angiosome of the saphenous branch was roughly four times smaller than previously reported (91.55 ± 63.98 cm²). A reason for this may again be generally the high variability of cutaneous angiosomes. It may also be due to the fact that many anastomoses exist, connecting all arteries around the knee with each other – especially on the medial side the DGA with the SMGA and the IMGGA as well as the recurrent tibial arteries.

SLGA

The SLGA originates from the popliteal artery at an average distance of 2.8–7.0 cm proximal to the knee joint line (Walton & Bunkis, 1984; Hayashi & Maruyama, 1990b; Wong et al. 2015; Morsy et al. 2018) or 4 cm proximal to the lateral condyle, usually a few millimeters below the origin of the SMGA (Hayashi & Maruyama, 1990b; Kirschner et al. 1998; Parvizi et al. 2016). Its diameter at origin measures 1.4–2.8 mm and the pedicle length is about 8 cm (Hayashi & Maruyama, 1990b; Parvizi et al. 2016). The SLGA subdivides into an anterior (also named superficial or patellar) and a posterior (also named deep or condylar) branch, and is responsible for the blood supply to the lateral femoral condyle, the lateral head of the gastrocnemius muscle, the vastus lateralis muscle and the biceps femoris muscle (Kirschner

Table 3 Classification of branching pattern of the DGA by Dubois et al. (2010) and Garcia-Pumarino & Franco (2014). Included were the reported frequency in current literature.

Type I – the three branches arise from a common trunk (actual DGA)	91.5% Rahmanian-Schwarz et al. (2011)
Type Ia – the DGA subdivides into three distal branches (osteoarticular, muscular, saphenous)	20–50% Ballmer & Masquelet (1998), Dubois et al. (2010), Hugon et al. (2010), Garcia-Pumarino & Franco (2014)
Type Ib – the muscular branch divides first, leaving behind an osteoarticular-saphenous trunk	16–25% Dubois et al. (2010), Hugon et al. (2010), Garcia-Pumarino & Franco (2014)
Type Ic – the saphenous branch divides first, leaving behind an musculo-osteoarticular trunk	20–44% Dubois et al. (2010), Iorio et al. (2012), Garcia-Pumarino & Franco (2014)
Type II – one of the branches of the DGA has a separate origin from the femoral artery	
Type IIa – the origin of the osteoarticular branch is isolated, the common arterial trunk is formed by the saphenous and muscular branches	3–25% Scheibel et al. (2002), Dubois et al. (2010), Hugon et al. (2010), Garcia-Pumarino & Franco (2014)
Type IIb – the origin of the saphenous branch is isolated, the common arterial trunk is formed by the muscular and osteoarticular branches	4–24% Acland et al. (1981), Hertel & Masquelet (1989), Ballmer & Masquelet (1998), Scheibel et al. (2002), Cavadas & Landin (2008), Dubois et al. (2010), Rahmanian-Schwarz et al. (2011), Iorio et al. (2012), Sananpanich et al. (2013), Garcia-Pumarino & Franco (2014)
Type IIc – the origin of the muscular branch is isolated, the common arterial trunk is formed by the saphenous and osteoarticular branches	0–40% Ballmer & Masquelet (1998), Dubois et al. (2010), Garcia-Pumarino & Franco (2014)
Type III – all three branches originate separately from the femoral artery	0–10% Ballmer & Masquelet (1998), Scheibel et al. (2002), Dubois et al. (2010), Garcia-Pumarino & Franco (2014)

DGA, descending genicular artery.

et al. 1998; Wong et al. 2015; Morsy et al. 2018). Furthermore, the iliotibial tract and the overlying skin at the superolateral side of the knee are supplied by the SGLA (Laitung, 1989; Hayashi & Maruyama, 1990b; Zhang, 1990; Pan et al. 2004; Fathi et al. 2008; Pan & Taylor, 2009; Nguyen et al. 2011; Boonrod et al. 2016; Parvizi et al. 2016; Morsy et al. 2018).

Apart from the DGA, the SLGA was the artery most often identified in this study. Its angiosome measured $107.87 \pm 48.42 \text{ cm}^2$ centered above the lateral femoral condyle an average of $3.54 \pm 3.63 \text{ cm}$ above the joint line, and $6.82 \pm 4.37 \text{ cm}$ lateral to the longitudinal axis with an average source vessel diameter of $1.54 \pm 0.52 \text{ mm}$.

SMGA

The SMGA originates from the popliteal artery at an average of 4 cm above the medial condyle, and supplies the posterior part of the medial condyle (Kirschner et al. 1998). Only in cases (11–15%) where the osteoarticular branch of the DGA is missing, the SMGA will provide the sole nutrition to the medial femoral condyle (Hertel & Masquelet, 1989; Hugon et al. 2010; Yamamoto et al. 2010; Sananpanich et al. 2013). In 30% the SMGA will provide no arteries to the medial femoral condyle (Hugon et al. 2010); in all remaining cases, both arteries will share its nutrition.

As the DGA is the more dominant artery in the superomedial region of the knee, the SMGA is said to lack a cutaneous branch (Bakri et al. 2008). However, skin perforators of this artery have been described in literature

(Sananpanich et al. 2013), and one of these perforators was also identified in the present study with a skin area of 33.51 cm^2 with a diameter of 1.2 mm. It was located 5 cm proximal of the joint line and 2 cm medial of the longitudinal axis of the leg.

ILGA

The ILGA originates from the popliteal artery at the level of the lateral meniscus. The height of its origin and course can range between the level of the lateral femoral condyle and the lateral meniscus (Kirschner et al. 1998; Taylor & Pan, 1998). The ILGA supplies the skin by perforating branches through the biceps femoris as well as on the lateral border of the quadriceps tendon, and anastomoses with the IMGGA in the skin through the arterial network of the patella (Pan & Taylor, 2009). On its course, the ILGA often forms anastomoses on the fibular head with both the PTRGA and periosteal branches from the anterior tibial artery (Kirschner et al. 1998; Taylor & Pan, 1998).

Angiosomes of the ILGA had a size of $48.87 \pm 36.43 \text{ cm}^2$ on average with a vessel diameter of $1.19 \pm 0.41 \text{ mm}$. They were centered above the lateral tibial condyle with an average of $4.43 \pm 3.96 \text{ cm}$ distal to the joint line and $9.17 \pm 2.09 \text{ cm}$ lateral to the longitudinal axis of the leg.

IMGGA

The IMGGA originates from the popliteal artery at the level of the upper edge of the medial tibial condyle and supplies

the latter (Kirschner et al. 1998; Taylor & Pan, 1998). The IMGGA provides cutaneous branches perforating at the lateral border of the sartorius muscle and at the medial border of the quadriceps tendon. In the skin in the patella region, it anastomoses with the ILGA (Pan & Taylor, 2009), medially with the DGA and the SMGA (Hertel & Masquelet, 1989) and on the surface of the tibial tuberosity with the ATRA (Kirschner et al. 1998; Taylor & Pan, 1998).

Angiosomes of the IMGGA showed an average size of $85.93 \pm 75.87 \text{ cm}^2$ with a vessel diameter of $1.32 \pm 0.51 \text{ mm}$. They were centered above the lateral tibial condyle with an average of $5.57 \pm 5.18 \text{ cm}$ distal to the joint line and $5.40 \pm 2.00 \text{ cm}$ medial to the longitudinal axis of the leg.

Clinical implications

Perforator flaps based on the DGA, its saphenous branch or the SLGA are well known in literature. Especially the angiosome of the saphenous branch has frequently been described as the basis for free skin flaps, neurovascular free flaps, osteocutaneous flaps or reversed-flow flaps, especially due to its long pedicle (Acland et al. 1981; Guan et al. 1985; Koshima et al. 1988; Torii et al. 1989; Bertelli, 1992a,b; Ballmer & Masquelet, 1998; Karamursel & Celebioglu, 2006; Iorio et al. 2012; Dai et al. 2013). More recently, the SLGA has been reported as source vessel in descriptions of the anterolateral-thigh flap – apart from the descending branch of the lateral circumflex femoral artery (Hayashi & Maruyama, 1990a; Yamada et al. 2014; Cadenelli et al. 2015), the posterolateral thigh flap (Laitung, 1989) and the lateral supragenicular pedicle perforator flap (Spokevicius & Janauskas, 1995; Taniguchi et al. 2009; Nguyen et al. 2011).

Throughout current literature, information is scarce looking at the perforator angiosomes of the inferior genicular arteries and their possible use as source vessels of flaps in reconstructive surgery. The pedicles of the ILGA and the IMGGA angiosomes are not as long as the superior arteries, as they course more perpendicular to the axis of the leg from their origin towards anterior. Nonetheless, they may be of use when designing cutaneous or fasciocutaneous flaps based on the results presented in this study. Apart from those standard uses, the possibility of vascularized tendinous grafts based on the IMGGA as already proposed (Zaffagnini et al. 2003; Hirtler et al. 2016) or combined osteotendinous grafts need further evaluation of their applicability in defect reconstruction.

Limitations

Some limitations need to be kept in mind when evaluating the results presented in this paper. Every study involving anatomical specimens has the benefit of evaluation or verification of hypotheses using methods that may rarely be performed *in vivo*. However, one has to keep in mind that the higher age of the body donors, the lack of muscle tonus

and the lack of blood pressure may influence the results. Also, due to the higher age of the body donors, the exclusion criterium of arteriosclerosis has to be adhered to quite strictly, as it would hamper correct evaluation of the vascular structures at hand. Despite this, only the DGA was identified in all specimens, all other arteries could not be successfully perfused one or more specimens. The main reason for this may be found in small blood clots clogging the respective artery, which were attempted to be dissolved by repeated perfusion of fluid with more or less success.

Conclusions

The complex distribution of perforator angiosomes of the anterior knee region was demonstrated. Based on the results presented in this study, not only the planning of existing perforator flaps in this region may be further facilitated, but also the development of flaps including the IMGGA or ILGA – also in combination with perforators from the recurrent tibial arteries – may be initiated.

Author contributions

LH contributed to concept and design, acquisition of data, data analysis and interpretation, drafting of the manuscript, critical revision of the manuscript, approval of the article. AL contributed to concept and design, acquisition of data, data analysis and interpretation, approval of the article. CR contributed to data interpretation, drafting of the manuscript, critical revision of the manuscript, approval of the article.

Conflict of interest

The authors have nothing to disclose.

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