Nonlinear Finite Element Simulations to Elucidate the Determinants of Perforator Patency in Propeller Flaps

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Abstract: The propeller-type flap design is increasingly used in reconstructive surgery for various regions of the body. To date, determinants of perforator patency when subjected to twisting have not been elucidated. We propose a simulation model to study parameters affecting perforator patency under such conditions. Nonlinear finite element procedure was used to simulate a perforator consisting of an artery and a vein with both ends fixed. A rigid body was attached to the top of the perforator for applying prescribed angular displacement. The effect of the following parameters on the pedicle patency was determined: (1) increasing angle of twist, (2) vessel stiffness, (3) vessel length, (4) diameter, (5) intraluminal pressure, and (6) the presence or absence of blood flow during twisting. Simulation results were reported in effective stress and strain on the twisted pedicle. In the context of perforator patency, effective strain, which is a measure of vessel deformation or collapse, is the more relevant outcome. The vein was more prone to occlusion because of its weaker wall and lower intraluminal pressure. Four factors that affected perforator patency were identified: angle of twist, intraluminal blood pressure, and perforator diameter and length. There was no significant difference whether twisting was performed prior to or after restoration of blood flow ($P > 0.05$). Therefore, to optimize condition for maintaining perforator patency, the angle of twist should be kept <180 degrees, perioperative blood pressure should be kept stable (avoiding periods of hypotension), and the selected perforator should be approximately 1 mm in diameter and >30 mm in length. We found that the propeller flap is a feasible design. This study defined the determinants of perforator patency and will serve as a useful guide when performing such flaps.

Key Words: perforator, propeller, flap, twisting, rotation, nonlinear finite element, simulation, hyperelasticity, novel, skin, island

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Microsurgeons have conventionally been taught to avoid twisting of the flap pedicle to prevent vessel kinking and occlusion. This is particularly important for veins which are low-pressure systems.[1] Techniques of raising fasciocutaneous flaps based on cutaneous perforators are increasingly reported in the literature. These flaps when used as local flaps are usually advanced in a V-Y or transposition manner.[2–4] Recently however, intentional rotating island flaps based on a single pedicle, twisting the artery and its vena comitantes in the process, have been reported.[5–10] In these so-called propeller flaps, a skin island isolated on a single perforator can be rotated up to 180 degrees, effectively transposing skin from one area to an area diagonally opposite the defect. The donor site can be primarily closed or skin grafted. This concept is particularly useful in areas where conventional local flaps are not readily available, such as the distal third of the leg and the ankle.[10] While this new concept of intentionally twisting the perforator introduced new possibilities into the reconstructive surgeon's armamentarium, safety concerns remained an obstacle to its widespread adoption. Although some successes with this technique have been anecdotally reported, success rates and long-term follow-up have yet to be reported in the literature. More importantly, determinants of perforator patency under such conditions have not been defined.

Nonlinear finite element analysis is a technique used to study structural integrity and has recently been successfully employed in reconstructive microsurgery.[11] We established a hypothesis that factors affecting vessel patency during sequential twisting included the following: (1) angle of rotation or extent of twist, (2) vessel stiffness, (3) diameter, (4) length, (5) intraluminal blood pressure and (6) twisting the perforator before or after blood flow was reestablished. This study was performed to verify this hypothesis using nonlinear finite element simulations. This model was subsequently used to define optimal conditions for maintaining perforator patency in propeller flaps.

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METHODS AND MATERIALS

Simulation was performed using LS-DYNA3D software (Livermore Software Technology Corp, Livermore, CA).

Methodology for Computer Simulation

Reference configuration for finite element model refers to the initial undeformed configuration from which simulation starts. The artery and vein were considered as cylindrical shell elements fixed at both ends (Fig. 1). Boundary conditions for the finite element model are important for effective and valid simulations. In the current simulations, the axial displacement of the distal ends of the artery and the vein were fixed to ensure that no tension was exerted on the perforators. A rigid body was attached to the top of the vessel for applying prescribed angular displacement. The mean intraluminal blood pressures for the artery and vein (except for cases where the effect of blood pressure were being investigated) were set at 90 mm Hg and 20 mm Hg, respectively.

Material Models

Although vessel walls are inelastic, inhomogeneous, anisotropic, and incompressible, approximations were introduced in our simulations to seek simplification when justified.[11] Hyperelasticity is one of the nonlinear elastic models and defines the relationship between stress and strain based on a stress-strain energy function. We used an isotropic Money-Rivivlin hyperelastic model (which is a generalization of the Neo-Hookean model) for the artery and the vein because large deformation was expected, and in such situation, a hyperelastic model will provide more accurate results. This model was defined as:

$$W = AI + BII$$

Where W is the strain energy density function, I and II are invariants of Cauchy Green tensor. A and B are constants. The Young's moduli $[E = 6(A + B)]$ for the artery and vein were derived from previous published works.[12–14] The constants A and B can be derived from these linear elastic models.

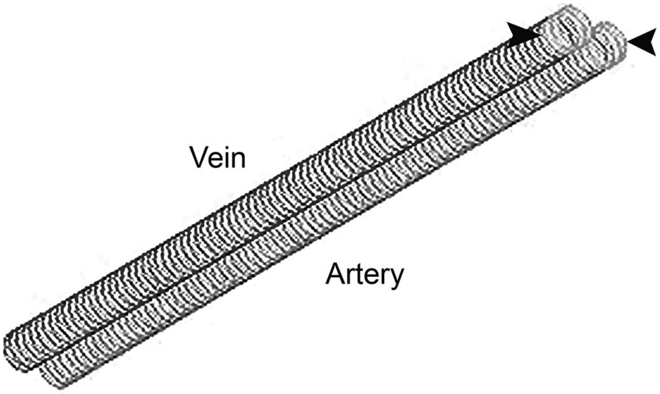

FIGURE 1. Reference configuration. The artery and vein were considered cylinders fixed at both ends. A rigid body was attached to the top of the vessel for applying prescribed angular displacement (arrow heads).

Geometrical Models

Arteries and veins with varying outer diameters were studied. The corresponding thickness and inner diameter can be decided by following formulae:

$$h_r = \frac{D_{outer} - D_{inner}}{D_{inner}};$$

where h_r is the relative wall thickness and was determined by microscopic measurements to be 0.1111 and 0.0417 for artery and vein, respectively. Shell elements of our finite element models were built based on these properties and the material models mentioned above. Figure 1 shows the model built.

Simulation was then performed to determine the effect of increasing angle of twist on effective strain of the vessels. To study the effects of the application of a tourniquet on these vessels, 2 scenarios were simulated. First scenarios involved the application of intraluminal blood pressure, followed by twisting of the vessels to designated angles. The sequence of events was reversed in the second scenario, with the vessels twisted to designated angles, followed by the application of blood pressure. The effects of vessel length, diameter, and intraluminal pressure on perforator patency as it was progressively twisted were in turn investigated by varying the parameter under study while keeping other parameters constant.

Statistical Analysis

Statistical analyses were performed using the SPSS statistical software (version 11.0; SPSS, Inc., Chicago, Illinois). The Mann-Whitney *U* test was used for comparison of means. A *P* value of <0.05 was defined as statistically significant.

RESULTS

The simulation results were reported in effective stress and strain on the twisted pedicle. The vessels' shape after twisting was monitored for buckling. Stress is defined as a force applied per unit area, and strain is defined a deformation of a body or structure as a result of the applied force. In the context of this study, the effective stresses and effective strains were used to characterize the vessels' biomechanical properties. However, the effective strain would be more relevant as this is a measure of vessel deformation, indicating collapse or occlusion of the vessel.

Effect of Angle of Rotation or Twist on Vessel Patency

Table 1 summarizes the resultant stresses and strains on the artery and vein as the vessels were sequentially twisted from 0 to 360 degrees (vessel diameter, 1 mm; length, 30 mm). Figure 2 shows the effective strain in the vein and artery. The following conclusions can be made: first, the stress and strain increase with increasing angle of twist (Fig. 3). Second, the vein is subjected to greater deformation (strain) because it has weaker walls and lower intraluminal pressure.

While there was a progressive increase in effective strain in the vein with increasing degree of twist, there was an

TABLE 1. Effective Stresses and Strains of Artery and Vein as the Vessels Were Sequentially Twisted From 0 to 360 Degrees (Vessel Diameter, 1 mm; Length, 30 mm)

	Effective Stress (MPa)		Effective Strain (%)	
Twisting Angle	Artery	Vein	Artery	Vein
45°	0.147	0.148	0.57	2.1
90°	0.22	0.21	0.84	3.14
135°	0.38	0.28	1.32	4.23
180°	0.493	0.42	1.84	6.50
225°	0.78	1.10	4.23	15.8
270°	0.872	1.18	3.85	15.9
315°	0.96	1.24	3.53	16.9
360°	0.883	1.01	4.49	14.8

In this simulation, perforator twisting was performed after application of intraluminal blood pressure.

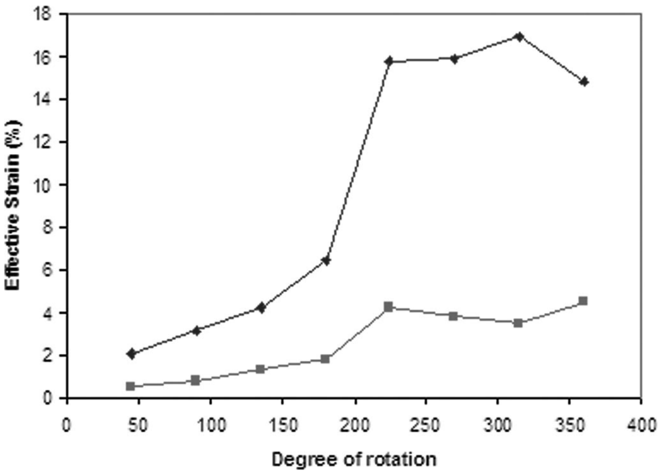

FIGURE 2. The effective strain in the vein (dark shade) and artery (light shade) as the perforator was sequentially twisted from 0 to 360 degrees (vessel diameter, 1 mm; length, 30 mm). Note the sudden increase in strain of the vein when the perforator was twisted beyond 180 degrees, indicating occlusion of the vein.

exponential increase beyond 180 degrees of twist as the vein collapsed. The artery, in contrast, with its thicker wall and higher intraluminal blood pressure, remained patent, with only small increases in effective strain with twisting up to 360 degrees. The stress was, however, greater in the artery because of his greater stiffness and Young's modulus (Fig. 4).

The Effect of the Presence or Absence of Blood Flow During Twisting

This effect was investigated by studying the resultant stress and strain of the vessel by inflating the vessel, followed by twisting versus twisting followed by inflating the vessel. Tables 1 and 2 showed the effective stresses and strains of the vessel in these 2 scenarios. These were no statistically significant differences in the stresses and strains of the artery and vein between the former and latter scenarios (comparing effective stresses of the artery, $P = 0.195$; effective stresses of the vein, $P = 0.645$; effective strains of the artery, $P = 0.279$; and effective strains of the vein, $P = 0.505$). Thus, in a clinical situation, release of the tourniquet prior to or after the flap was rotated into place would not significantly affect patency rates.

Effect of Vessel Length

Figure 5 showed the effective strain of the artery and vein as the length increased. Note the sudden decline in the vein effective strain as the length of the perforator was increased beyond 3 cm. Thus, to minimize strain on the vein, the perforator should be mobilized or freed to obtain a length of >3 cm.

Effect of Vessel Diameter

The vessel diameters were changed to study their effects. Figure 6 demonstrated the effective strain on the artery and vein with same length of 30 mm when twisted to 180 degrees. The strain on the vein declined as the vessel size was increased from 0.5 mm to 1 mm. Subsequently, as the vessel diameter was increased further, the effective strain progressively increased. Thus, the ideal diameter to minimize perforator deformation when twisted, other parameters being equal, was approximately 1 mm.

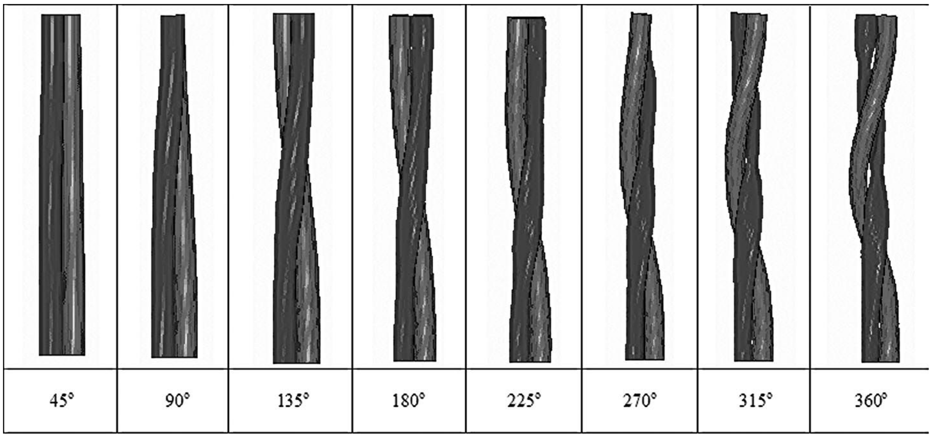

FIGURE 3. Strain on the vein (dark shade) was evident as the perforator was sequentially twisted. The vein was occluded beyond 180 degrees while the artery (light shade) remained patent up to 360 degrees.

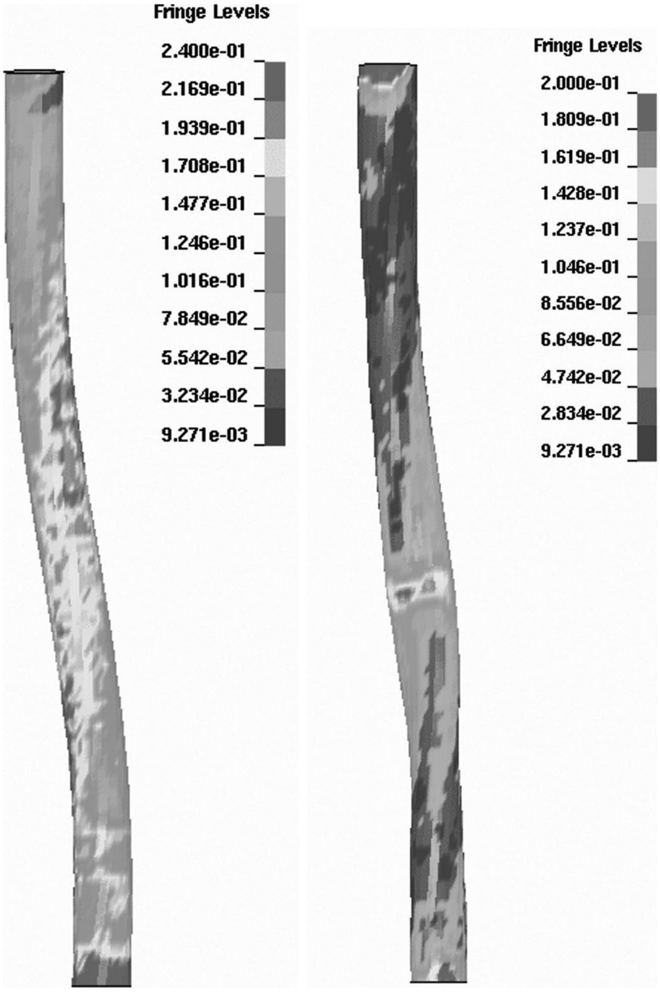

FIGURE 4. The stress on the artery was greater than that in the vein (vessel diameter, 1 mm; length, 30 mm at 180 degrees' twist). The artery's greater stiffness allowed it to resist deformation (strain) and remain patent. The vein, on the other hand, deformed or strained more readily under stress.

Effect of Intraluminal Pressure

Mean intraluminal pressure, particularly in the delicate veins, is the main factor in resisting vessel deformation. Predictably, as shown in Figure 7, as intraluminal blood pressure was increased, effective strain decreased. Therefore, maintaining an adequate blood pressure perioperatively is important in a propeller-type flap. Venous congestion, which in turn raises the venous pressure, tends to maintain patency of the vein. At what point this congestion reaches a critical level such that it impedes arterial inflow and ultimately causes flap demise is yet to be defined. However, to collaborate with a previous report, one should appreciate that some venous congestion may be inherent with this type of flap because of the venous hypertension needed to keep the veins patent.

TABLE 2. Effective Stresses and Strains of Artery and Vein as the Vessels Were Sequentially Twisted From 0 to 360 Degrees (Vessel Diameter, 1 mm; Length, 30 mm)

	Effective Stress (MPa)		Effective Strain (%)	
Twisting Angles (º)	**Artery**	**Vein**	**Artery**	**Vein**
45°	0.427	0.238	1.38	3.47
90°	0.527	0.350	1.90	4.77
135°	0.618	0.420	2.06	5.81
180°	0.49	0.538	1.61	7.7
225°	0.94	0.850	3.80	12.7
270°	1.16	1.132	6.40	19.5
315°	1.32	1.180	6.50	16.7
360°	1.40	1.460	8.10	21.0

In this simulation, perforator was twisted first, followed by application of intraluminal blood pressure. No significant difference was noted between the corresponding values in Table 1 vs Table 2. This indicated that in a clinical situation, release of the tourniquet prior to or after the flap was rotated into place would not significantly affect patency rates.

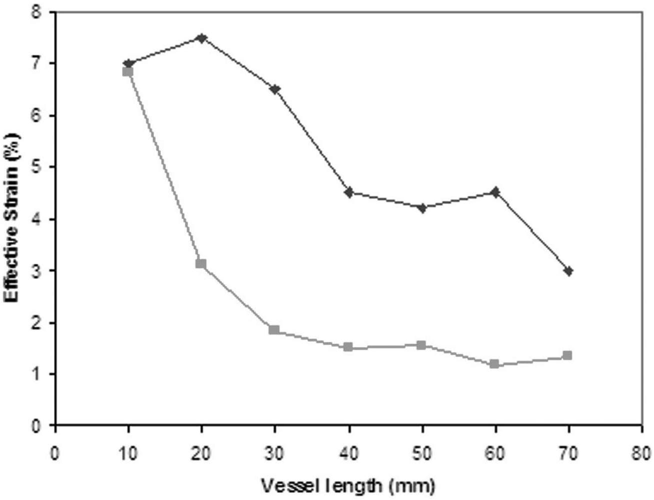

FIGURE 5. Plot of the effective strain on the artery (light shade) and vein (dark shade) as the perforator (1-mm-diameter perforator at 180 degrees' twist) was progressively lengthened from 10 mm to 70 mm. Note the sudden decrease in vein strain as the perforator was lengthened beyond 30 mm.

Clinical Application of Simulation Results

A 34-year-old man fell from height and presented with an open dislocation of the left ankle. Reduction stabilization with an external fixator was performed. Postoperative skin-edge necrosis and infection resulted in an exposed ankle joint. Coverage with a propeller-type flap based on the lateral leg perforator was planned. Two perforators were located by handheld Doppler, and the propeller flap was designed centered on the more proximal perforator. A posterior incision was made first to evaluate the perforators. A single small perforator (0.4 mm), corresponding to the proximal perforator, was found. No other perforators were seen in the vicinity. An anterior incision was therefore made, and a larger perforator (1.0-mm diameter) was noted. Based on our simulation study, the larger perforator was therefore selected. After mobilizing the perforator for a length of 1.5 cm, the perfo-

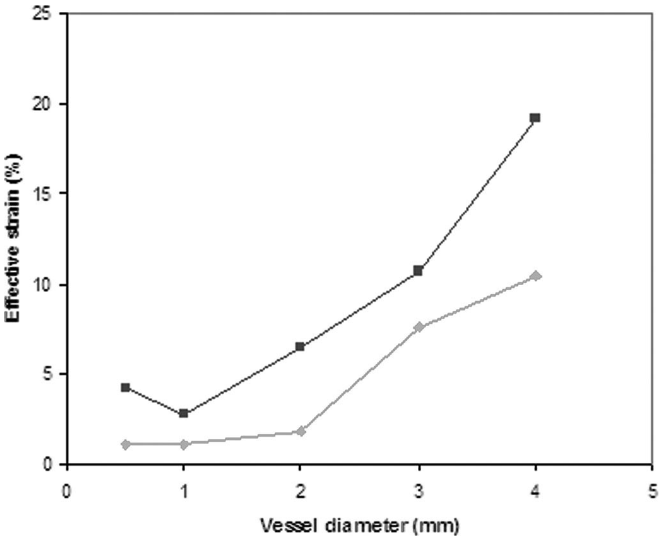

FIGURE 6. Plot of the effective strain on the artery (light shade) and vein (dark shade) as the perforator (30-mm length at 180 degrees' twist) diameter was increased from 0.5 mm to 4.0 mm. Minimum strain was noted at 1 mm, indicating this to be the ideal diameter for propeller flaps.

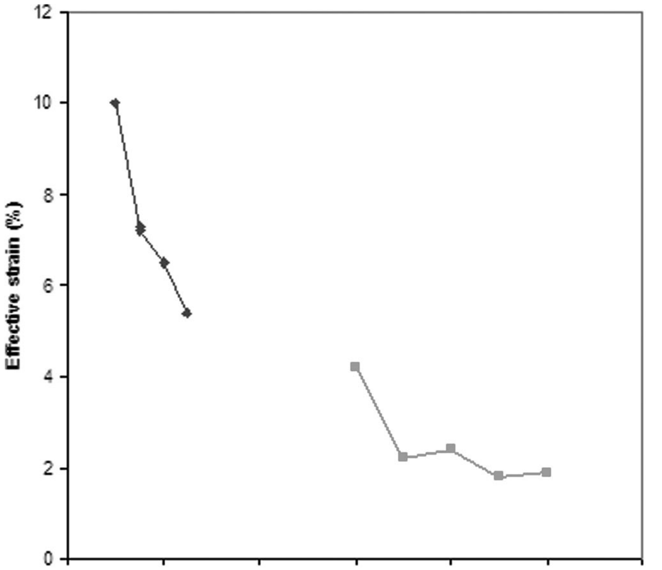

FIGURE 7. The effect of increasing intraluminal pressure on effective strain of the artery (light shade) and vein (dark shade). Increasing intraluminal pressure decreases vessel deformation. This effect is particularly dramatic in the soft veins, in which the blood pressure played a major role in resisting vessel deformation. Maintaining an adequate perioperative blood pressure is therefore important in propeller flaps.

rator pierced the ankle retinaculum. As the length was insufficient to safely rotate the flap, the ankle retinaculum was opened to mobilize the perforator further. The perforator was traced to its origin at the anterior tibial artery and measured 4.5 cm in length. The flap was islanded and rotated 180 degrees to cover the ankle defect (Fig. 8A, B). The donor site was skin grafted. After rotation, the flap was slightly congested. The leg was elevated postoperatively and congestion gradually improved over the next few days. The flap healed uneventfully, and when reviewed at 6-month follow-up, complete flap survival was noted (Fig. 8C).

DISCUSSION

The propeller concept was first introduced by Katsaros[5] in 1982, where he successfully raised an island tensor fasciae latae flap based on its pedicle and rotated the flap 180 degrees to cover a chest-wall defect. This technique was subsequently largely forgotten until 1991, when Hyakusoku et al[6] described a subcutaneous pedicle flap that can be rotated to about 90 degrees for release of burn contractures. However, because of the bulkiness of the subcutaneous pedicle, the amount of rotation that can be achieved is limited.[6,7] The advent of perforator flaps has renewed interest in this flap design, with island-skin flaps based solely on a single perforator successfully used as perforator propeller flaps.[8–10] Perforator dissection minimized bulkiness around the pedicle and allowed it to rotate or twist freely. The use of cutaneous perforators (be it direct cutaneous, septocutaneous, or musculocutaneous) allowed this design to be used virtually anywhere in the body, extending the use of propeller flaps for coverage of defects in various parts of the body. This technique has therefore garnered increasing interest as a versatile flap concept. This is particularly so in the distal third of the leg, where conventional local flaps are limited and unreliable.[10] It also provides an additional lifeboat in cases where other options have been expended, such as in recurrent pressure sores.[9] However, removing tissue wrapping around the perforator also made it more susceptible to kinking and occlusion. Furthermore, the idea of intentionally twisting the pedicle seemed counter to the fundamental principles of reconstructive microsurgery.[1,15,16] While factors determining perforator patency are variable, depending on physical conditions prevailing in each individual case, this study defined conditions that are important to maximize the probability of maintaining vessel patency and therefore serves as a useful guide when performing such flaps.

This simulation study found that the propeller perforator flaps are feasible as perforators can safely be twisted up to 180 degrees. We found in our study that the veins are much more susceptible to occlusion and that factors affecting vessel patency included the angle of rotation of the perforator, the perforator's diameter and length, and intraluminal blood pressure. To maximize chances of maintaining vessel patency, one should therefore select perforators with a diameter of around 1 mm and of adequate length (>3 cm). The latter recommendation would entail aggressive mobilization of perforators toward their origin to obtain an adequate pedicle length. Also, the lesser the angle of rotation or twist, the lesser the degree of stress and consequent strain on the vessels. Therefore, when designing propeller flaps, one that would entail taking the perforator through a lesser angle of

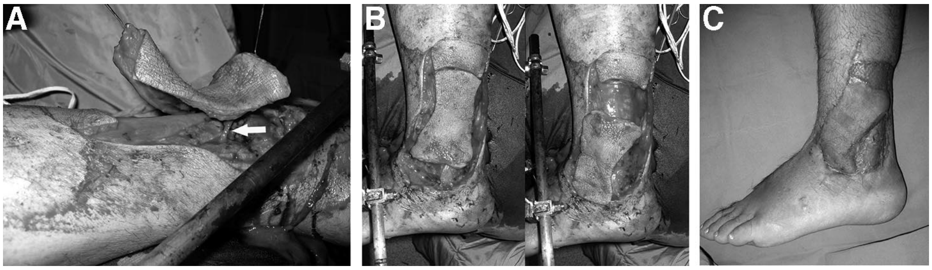

FIGURE 8. A, A 1-mm-diameter perforator was selected as the flap pedicle (arrow). To obtain an adequate length to safely twist the pedicle, this was dissected through the ankle extensor retinaculum and traced to its origin at the anterior tibial artery. B, The flap rotated 180 degrees to cover the defect. Extra soft tissue was included at the tip of the flap. This was deepithelialized and used to fill dead space at the defect site. The flap was slightly congested at completion of inset. C, Patient at 6-month follow-up, with complete survival of the flap.

twist would be preferable. In a clinical setting, the perforator would usually not be needed to twisted more than 180 degrees as the flap can be brought into the defect either by a clockwise or counterclockwise rotation. If one needs to rotate more than 180 degrees to bring the flap into the defect, one should reverse the direction of rotation. This would twist the perforator through a lesser angle.

Four previous experimental studies have been designed to study the effect of pedicle twisting on flap survival.[17–20] Izquierdo et al[18] concluded that twisting of up to 180 degrees did not significantly affect patency of arteries or veins. Demir et al[20] reported similar results and concluded that the perforator can tolerate twisting up to 180 degrees. Demirseren et al[19] even found twisting of up to 360 degrees had no effect on flap survival in their study. Salgarello et al,[17] however, showed that twisting as little as 90 degrees reduces patency rates, particularly in veins. These somewhat contradictory findings can be attributed to 2 basic factors: first, the differing experimental design used, with different choices of vessels studied and the presence of an anastomotic repair in some of the vessels prior to twisting; second, failure to standardize factors noted to be important in determining perforator patency noted in this study may have contributed to the discrepancy noted. From the literature and demonstration at recent meetings, propeller flaps (with rotation up to 180 degrees) have been shown to be a viable and versatile.[5–10] It stand to reason therefore that attention to factors such as angle of rotation, perforator diameter, length, and perioperative blood pressure are all important to maximizing success.

Salgarello et al[17] noted that the odds ratio of venous occlusion was 226 times versus 10 times for the artery at 270 degrees' twist. In collaboration with clinical observations, therefore, venous congestion is an inherent problem with the propeller-type design. It is difficult to judge what degree of congestion is acceptable and what would herald impending flap demise. The color of propeller flaps may be darker than what would commonly be deemed acceptable for other flap designs. In this respect clinical judgment remains the final arbiter. In cases where venous congestion is severe despite optimizing pedicle conditions, 2 options may be taken: first, the vein and artery may be cut, untwisted, and reanastomosed in an untwisted position. Both vein and artery would need to be cut as it is difficult to untwist the vein with the artery still in continuity. This approach is particularly applicable in cases where the vein and artery are sizable (>1 mm). For a true perforator propeller flap, this is technically demanding as this would entail separation of the perforator artery from its vena comitantes and repair of the vein and artery with supermicrosurgery technique in a perforator-to-perforator manner.[21] A second option would be to abandon the propeller flap and return the skin island to its native position and use an alternative flap for coverage.

Limitations inherent in simulation studies should be noted. This study assumed uniform vessel stiffness. In clinical situations, particularly when the perforators are musculocutaneous perforators, intramuscular dissection can potentially create areas of weakness that would preferentially crumble when twisted. Care should therefore be taken during dissection to avoid damaging these delicate vessels. The presence of an anastomosis can also create localized areas of altered physical properties and may predispose to kinking. Also, physical properties of arteries and veins may vary tremendously. One such example is calcification of vessels in elderly and diabetic patients. Therefore, it is important to remember that while this study defined factors that determined vessel patency, these factors were defined in a relative manner and are meant as general guidelines. Finally, meticulous technique and clinical judgement remains of paramount importance when performing such flaps.

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