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Keystone perforator island flaps in the reconstruction of lower limb defects resulting from shrapnel and mine-explosive combat injuries. Case series

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In the conditions of warfare in Ukraine, the question of providing medical services to injured civilian and military is especially relevant and severe. In plastic surgeons` professional activities, the task is to restore extensive and deep wound defects in a short term and with a high degree of damaged organ`s restoration, especially supporting function. In this article the authors describe their experience with local keystone perforator island flaps, which are used to reconstruct skin and soft tissue defects of the lower limbs caused by combat injuries.

Patients and methods. The authors conducted a retrospective review of 49 keystone perforator flaps for 28 patients (26 men and 2 women) who received treatment in the clinic for bullet, shrapnel, and mine-explosive injuries between 2014 and 2022.

Results. In all cases, extensive wound defects were completely closed during a single-stage surgical procedure, and the patients were discharged after recovery. Non-critical complications required secondary sutures in two cases (4 %), extending the duration of treatment by 6 days. The time spent in the operating room on the transposition of one flap ranged from 40 to 95 min (mean: 67 min).

Conclusions. The findings of the study show that local keystone perforator island flaps are highly effective in the successful reconstruction of lower limb defects caused by combat wounds. The keystone perforator island flap technique requires basic preoperative preparation of the patient, is easy-to-use, and exhibits a fairly high level of reliability at the same time. In most cases, keystone perforator island flaps provide primary and single-stage closure of a large defect in the thigh, in the area of the knee joint, and in the lower leg in the absence of secondary defects that are common at donor sites when alternative techniques are chosen.

Keywords
reconstructive surgery, perforator flap, combat injury, wounds, keystone flap.

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In the conditions of warfare in Ukraine, the question of providing medical services to injured civilians and military personnel is especially relevant and urgent. In the short term, plastic surgeons deal with restoring extensive and deep wound defects, which require a high degree of damaged organ restoration, especially supporting function [13, 20]. As the authors note, lower limb injuries range from 38.3 % to 91.0 % [9, 11, 14]. At the same time, surgical closure of wound defects is an urgent and rather difficult task, especially when specialists face the need to select a surgical method for closing deep and extensive wound defects [14, 16]. The ideal reconstruction for lower limb defects should be based on the following concept: replace «like to like» tissues and minimize donor-site morbidity, achieving the best possible aesthetic and functional outcome. In this regard, the demand for surgical

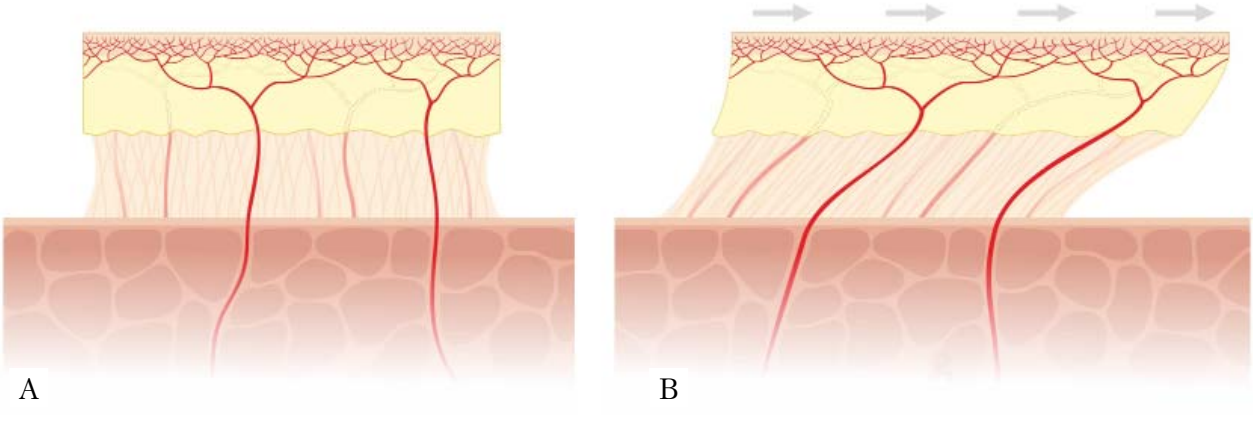

Figure 1. **Scheme of arterial and neurovascular connections of the raised keystone perforator island flap, based on the concept of angiotome: before (A) and after (B) displacement of the flap to the right. The remaining microvascular and axillary connections, along with arterial perforators, provide immediate vascular augmentation in the tissues after plastic surgery (IVA)**

transplantation of local flaps is growing. The technique provides a higher quality of single-stage wound defect closure than the transplantation of a skin graft, even if it includes the reconstruction of the dermal layer with a biomatrix [2, 18]. The keystone perforator island flap technique is an exclusive and effective method in reconstructive surgery [4, 5, 7]. The study presents the keystone perforator island flap technique and options for its clinical application in the reconstruction of lower limb defects resulting from shrapnel and mine-explosive combat injuries.

Objective — to provide the fastest and most effective closure of skin and soft tissue defects of lower limbs caused by combat injuries by using local donor resources according to the «like to like» reconstruction concept.

The keystone perforator island flap: description, design, and dissection technique

The method was developed by Behan et al. [4, 5, 7]. According to his studies on anatomical material and clinical practice, the majority of axillary perforating arteries have additional microscopic venous, neurovascular, and arterial plexuses closely connected to each other (Fig. 1). This fact indicates the potential for improving the nutrition of the marginal and adjacent territories of the skin and soft tissues, thereby significantly increasing the area and survival of the excised local keystone perforator island flap. The preserved arterial and neurovascular connections of the raised keystone perforator island flap can be seen without magnification intraoperatively (Fig. 2).

The classic keystone perforator island flap is planned according to the shape of the surface in the form of a trapezoid with a curved arch along the wound defect. Actually, the similarity between the shape of the flap and the stone arched blocks, which were mounted above the windows and passages by Roman architects, determined its name. The surgeon's clinical evaluation of the surrounding tissues is a sufficient condition for the formation of the flap geometry. It is not mandatory to confirm the functional validity of each perforator using CT with angiography or Doppler examination. It can be visualized intraoperatively and preserved during subsequent dissection.

After excision of the edges of the wound and radical debridement, it is necessary to give the wound defect an elliptical shape (Fig. 3). The marking of the flap is performed relative to the arc bordering the wound defect along its longest side.

The choice of donor site as well as its direction relative to the wound are determined by the

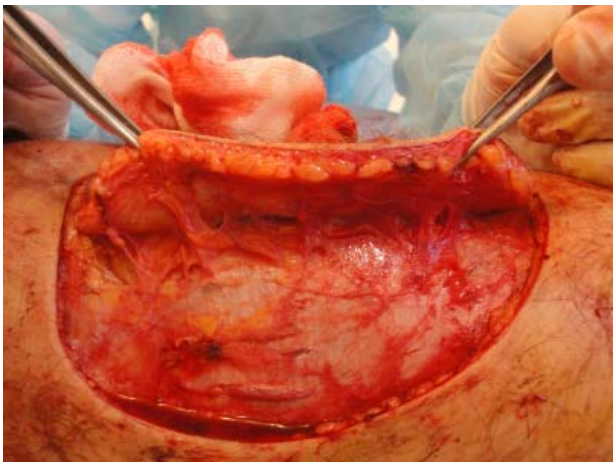

Figure 2. **Intraoperative view of the preserved arterial and neurovascular connections of the raised keystone perforator island flap in the thigh area**

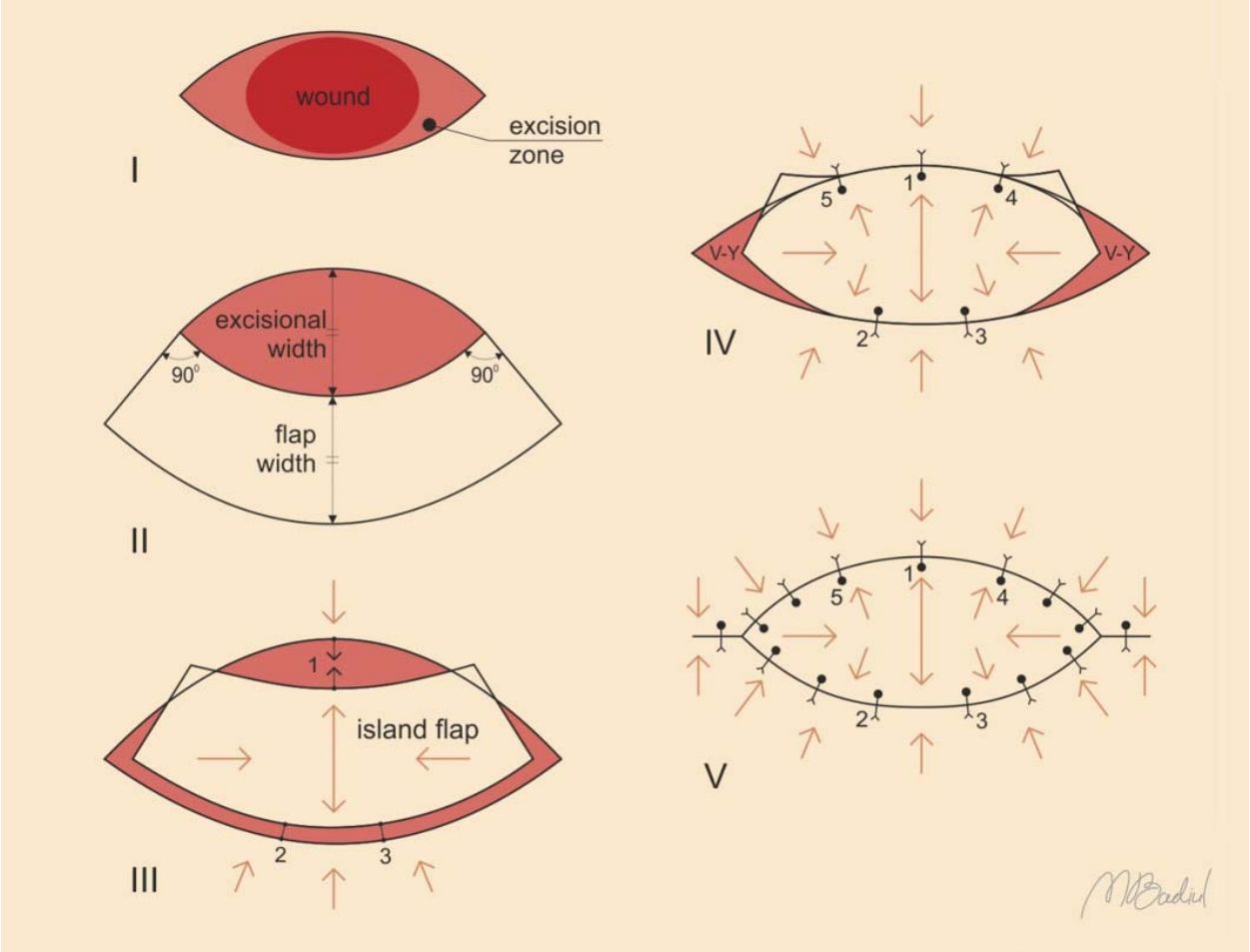

Figure 3. **Scheme of wound preparation techniques and plastic procedures for skin defect closure using the keystone perforator island flap:** I — surgical treatment of the wound with elliptical excision of the edges of the wound defect; II — the width of the excision of the wound defect must coincide with the width of the planned flap; III — the flap is cut out like an island with a complete crossing of the skin and subcutaneous tissues. The subsequent blunt preparation in the suprafascial space maximally preserves the available perforators and connected axillary plexuses, and at the same time makes it mobile, ready for spatial redistribution; IV — scheme of spatial redistribution of covering tissues without significant tension when moving the keystone island flap to the area of the wound defect and the sequence of applying key sutures; redistribution directions are indicated by arrows; V — the final stage of adaptation of the flap and suturing of the lateral fragments of the defect using the V-Y plastic maneuver without tissue tension

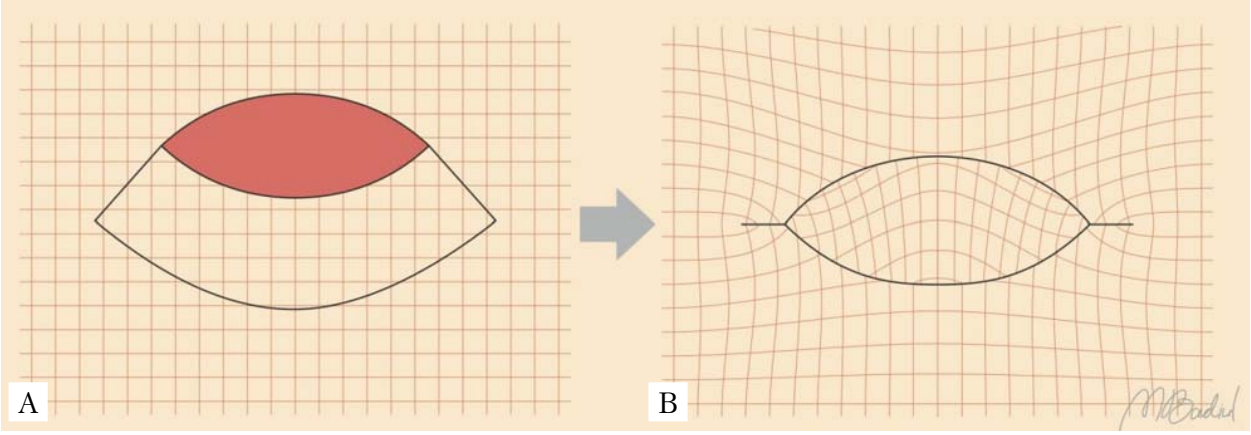

Figure 4. **Scheme of the distribution of covering tissues during plastic closure of wound defects with a keystone perforator island flap: A — before the flap is moved, the scale grid is not deformed; B — after moving and suturing the flap to the edges of the wound defect, deformations of the scale grid are visualized, which demonstrates a change in the geometry of various areas of the flap and surrounding tissues**

Table. **Patient characteristics**

PN	Age, years	Sex	FN	Aetiology	Localization	Wound size, cm	Flap size, cm	Complication
1	22	M	1	Mine shrapnel	Thigh	23×7	29×8	–
2	45	M	2	Mine shrapnel	Shin	15×8	13×4	–
			3	Mine shrapnel	Shin	24×5	27×8	–
3	36	M	4	Bullet	Shin	15×6	16×6	+
4	33	M	5	Bullet	Shin	8×7	17×7	–
			6	Bullet	Shin	5×3,5	9×3,5	–
5	28	M	7	Mine shrapnel	Thigh	14×7	23×7	–
			8	Mine shrapnel	Shin	17×6	35×6	–
6	35	M	9	Mine shrapnel	Shin	15×5	20×7	–
			10	Mine shrapnel	Shin	10×4	20×7	–
7	23	M	11	Mine shrapnel	Thigh	15×6	26×7	–
8	33	M	12	Mine shrapnel	Thigh	15×10	20×8	–
			13	Mine shrapnel	Thigh	15×10	13×9	–
9	47	M	14	Mine shrapnel	Knee joint	8×4	6 ×5	–
10	27	M	15	Mine shrapnel	Shin	10×4	12×5	–
			16	Bullet	Shin	6×3	11×3	–
11	29	M	17	Bullet	Thigh	15×5	18×6	–
			18	Bullet	Thigh	14×4	16×6	–
12	22	M	19	Mine shrapnel	Thigh	23×7	29×8	–
13	25	M	20	Mine shrapnel	Shin	15×7	16×7	–
			21	Mine shrapnel	Shin	12×7	12×7	–
14	21	M	22	Mine shrapnel	Shin	9×4	16×4	–
15	23	M	23	Mine shrapnel	Shin	9×4	15×5	–
16	43	M	24	Bullet	Thigh	7×4	13×5	–
			25	Bullet	Thigh	9×6	20×6	–
			26	Bullet	Thigh	11×6	18×7	–
17	25	M	27	Bullet	Thigh	10×5	13×5	–
18	19	M	28	Mine shrapnel	Thigh	7×6	9×6	–
			29	Mine shrapnel	Thigh	8×6	10×6	–
			30	Mine shrapnel	Shin	10×8	14×10	–
			31	Mine shrapnel	Shin	9×6	11×8	–
			32	Mine shrapnel	Thigh	12×6	14×7	–
			33	Mine shrapnel	Shin	8×6	10×6	–
			34	Mine shrapnel	Shin	16×8	18×9	–
19	38	M	35	Mine shrapnel	Shin	10×4	12×5	–
20	26	M	36	Mine shrapnel	Thigh	12×8	15×9	–
21	48	M	37	Mine shrapnel	Thigh	6×3	8×4	–
22	22	M	38	Mine shrapnel	Thigh	8×5	10×5	+
23	58	F	39	Mine shrapnel	Knee joint	10×4	12×6	–
24	21	M	40	Mine shrapnel	Shin	8×4	9×4	–
			41	Mine shrapnel	Shin	4×3	5×4	–
25	37	M	42	Mine shrapnel	Shin	8×5	10×5	–
			43	Mine shrapnel	Shin	5×4	7×4	–
26	20	M	44	Mine shrapnel	Shin	5×3	6×3	–
27	30	M	45	Mine shrapnel	Thigh	12×7	14×7	–
			46	Mine shrapnel	Thigh	9×4	11×6	–
			47	Mine shrapnel	Thigh	12×5	14×6	–
28	21	F	48	Mine shrapnel	Thigh	15×6	17×6	–
			49	Mine shrapnel	Thigh	14×7	18×7	–

Note. PN — patient number; FN — flap number.

mobility of the skin. For the lower limbs, the best choice is the formation of a flap behind the defect, where the most mobile fascial-muscular compartments are located. According to the figure (see Fig. 3; position II), the width of the excision of fthe wound defect must coincide with the width of the planned flap. However, the flap can differ considerably in size in terms of length. The step is caused by the fact that the flap expands in the form of a trapezoid to its edge, distant from the wound defect. A bordering incision along the perimeter forms an island-like flap with complete transection of the skin and subcutaneous tissues. The subsequent blunt preparation in the suprafascial space maximally preserves the available perforators and associated axillary plexuses (see Fig. 1, 2) and, at the same time, makes them mobile, ready for plastic distribution to the area of the wound defect. The sequence of stitching is also important. The flap is first adjusted in width with the application of key stitches in the central part, and then the displaced material is distributed and fixed on both sides of the center with subsequent stitches, with arrows indicating the directions of distribution of covering materials. The final stage of flap adaptation and suturing of the lateral fragments of the defect using the V-Y plastic maneuver is carried out without tissue tension. The diagram of the distribution of covering tissues during plastic closure of wound defects with a keystone island flap demonstrates the change in the geometry of the surface of various areas of the flap and surrounding tissues with the help of a scale grid (Fig. 4). When suturing the skin, tissue tension should not exceed 14.2 g/mm in order to prevent blood vessel spasm and thrombosis [17, 19]. Clinically, the skin tension should not cause paleness around the wound edges and the area where the skin is captured by a tool or suture.

Patients and methods

A clinical review of 28 patients (26 (93.0 %) men and 2 (7.0 %) women) was conducted from 2014 to 2022. Their ages ranged from 19 to 58. Patients suffered bullet or shrapnel injuries and mine-explosive injuries to the lower limbs. Initially, all patients received medical care at the mobile hospitals or local hospitals, and then they were transferred to a specialized center for the final plastic closure of wound defects. Patients underwent plastic surgery for reconstruction of the lost skin and soft tissues using a local perforator keystone flap. 49 flap surgeries were performed: 11 patients had 2 wounds that were closed instantly, 2 patients had 3 wounds, and 1 patient had 7 wounds. Concerning localization of defects, there were 23 (47.0 %) flaps on the thigh, 2 (4.0 %) flaps on the knee, and 24 (49.0 %) flaps on the tibia (Table).

Results

In all cases, significant lesion abnormalities were fully closed in one step and patients were discharged after convalescence. All flaps took root; post-operative flow complications were not critical and were eliminated. In two cases (4.0 %) of non-critical complications, secondary sutures were used, and treatment was prolonged by six days. The operating time spent on one flap transposition ranged from 40 to 95 minutes (the average time was 67 minutes). The displaced perforated local flaps were similar in structure and color to the surrounding tissue; they did not alter the contours of the donor and recipient zones. The absence of secondary defects that are common at donor sites when using alternative procedures was a feature of the aesthetic outcome of this method. Consequently, using perforator flaps in reconstructive surgery made it possible to simultaneously close the wound defect and the donor area without changing the contours of the body or limbs.

Case 1

Patient K., a 22-year-old civilian woman, was admitted to the clinic with a shrapnel and mine-explosive injury to her lower extremities. On the left side of the thigh there was a through-and-through wound, and on the right side of the wound, a blind canal ran

Figure 5. **View of shrapnel and mine-explosive injuries to the buttocks and lower extremities after NPWT**

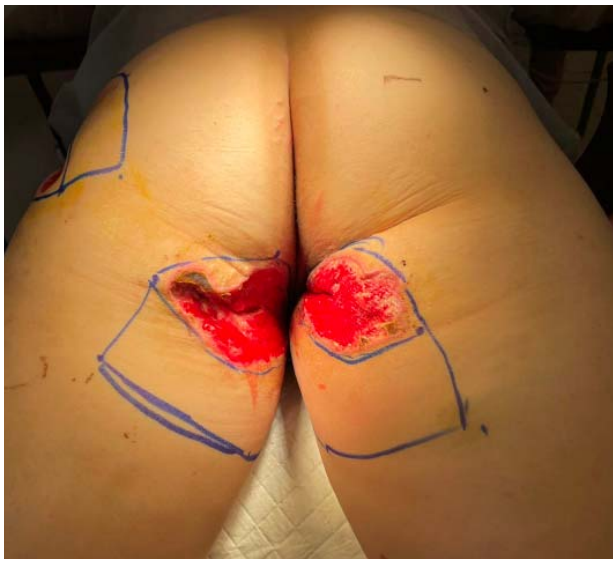

Figure 6. **Design and markup of the three planned keystone island flaps**

Figure 7. **Intraoperative digital photo. The flaps were adapted and sutured to the edges of the three wounds without tension**

Figure 8. **Side view on the left. The result of treatment 18 days after surgery**

Figure 9. **View from the back. All wounds were closed without altering the contours of the buttocks and lower extremities**

along the medial surface in the upper 1/3. After the removal of non-viable tissues and negative pressure wound therapy (NPWT) for 5 days, deep and extensive defects located on the left side of the buttock and thighs were covered with granulations (Fig. 5). The keystone perforator island flap technique was chosen in order to close the wounds (Fig. 6). Three flaps were formed according to the island type, with a complete dissection of the skin along the perimeter and mobilizations that provided tissue mobility. The flaps were adapted to the edges of the wounds and fixed with tension-free sutures (Fig. 7). The postoperative course went smoothly; the sutures were removed on the 14th day, and the patient was discharged after recovery. The observation 18 days after surgery (Fig. 8, 9) demonstrates adequate restoration of the covering tissues without altering the contours of the buttocks and lower extremities. The newly formed covering tissue is quite elastic and mobile and exhibits sensitivity to various stimuli. The function of the lower extremities is fully restored.

Case 2

Patient L., a 61-year-old civilian woman, was admitted to the clinic with a shrapnel and mine-explosive injury to the knee area of her left lower extremity.

Figure 10. **View of the shrapnel and mine-explosive injury to the knee area of the left lower extremity. The wound did not heal for 6 weeks after simple suturing. The tissue surrounding the wound is inflamed**

Figure 11. **Design and markup of the radical debridement area and planned keystone perforator island flap**

Figure 12. **Intraoperative digital photo. The flap was adapted and sutured to the edges of the wound without tension**

Figure 13. **Side view on the left. The result of treatment 61 days after surgery. The wound was closed without altering the contours of the knee area**

Previously, the wound was sutured at the local hospital without effect. The wound did not heal for 6 weeks (Fig. 10). It was planned to perform a radical debridement, revision of the wound, and its closure with a keystone perforator island flap, with the effect of revascularizing damaged structures in the functionally active zone of the joint (Fig. 11). The flap was formed as an island and moved to the area of the knee joint, where it was fixed with sutures to the edges of the wound defect without tension (Fig. 12). Immobilization of the lower limb in a splint for up to 4 weeks, the sutures were removed on the 14th and 20th days, and the patient was discharged after recovery. Two months of follow-up after surgery demonstrated adequate restoration of covering tissues without altering the contours of the lower limb (Fig. 13) and with complete restoration of the knee joint function (Fig. 14). The patient walks on his own with no special devices.

Figure 14. **The function of the lower extremities was fully restored**

Case 3

Patient M., a 38-year-old military man, was admitted to the clinic with a shrapnel and mine-explosive injury to the left shin (Fig. 15). It was planned to perform a radical debridement and wound closure with a perforator keystone island flap (Fig. 16).

After traditional mobilization with preservation of perforators and coaxial connections, a flap was adapted and sutured to the edges of the wound on the medial surface of the shin without tension (Fig. 17). The postoperative course went smoothly; the sutures were removed on the 14th day, and the patient was discharged after recovery. The observation 6 months after surgery (Fig. 18) demonstrates adequate

Figure 15. **View of the shrapnel and mine-explosive injury to the shin upon admission to the clinic**

Figure 16. **Design and markup of the planned keystone perforator island flap**

Figure 17. **Intraoperative digital photo. The flap was adapted and sutured to the edges of the wound on the medial surface of the shin without tension**

Figure 18. **Medial side view on the left shin. The result of treatment 6 months after surgery. The wound was closed without altering the contours, and the lower limb function was fully restored**

restoration of the covering tissues without altering the contours of the lower extremity. The newly formed covering tissue exhibits stability to various stimuli, is quite elastic and mobile, easy to fold, and has a hairline (Fig. 19), fulfilling the «like-to-like» principle.

Figure 19. **The restored skin is elastic, easy to fold, exhibits stability to various stimuli, and has a hairline, fulfilling the «like-to-like» principle**

Discussion

Since 2014, combat injuries to the lower limbs have become a serious challenge for doctors of various specialties, including plastic surgeons [11, 13, 20]. Our preliminary results with regard to the reconstruction of lower limb defects caused by shrapnel and mine-explosive combat injuries using keystone perforator island flaps demonstrated a sufficiently high efficiency in the plastic closure of extensive wound defects in the injured areas of the thigh, knee joint, and lower legs. The accumulated experience allows us to affirm that the keystone perforator island flap is a priority method for one-step wound closure in the lower extremities. The use of alternative methods of plastic closure of wound defects in the lower extremities has been described in detail in previously published works [1, 15]. Local keystone perforator island flaps can be considered one of the primary methods for plastic closure of extensive combat wound defects at different anatomical locations, provided that the tissue surrounding the defect is intact and usable as a donor resource [3, 16].

One-stage reconstruction of extensive soft tissue defects is recognized by different authors as a priority in plastic surgery compared to multi-stage surgical interventions [16—18]. This reconstruction provides the fastest primary closure of the soft tissue defect. In order to increase the effectiveness of treatment in both the functional and aesthetic aspects, the keystone perforator island flap can become an alternative to skin autografts in terms of the quality of the restored covering and to two-stage cross-plastic methods or methods associated with the imposition of microvascular anastomoses, while significantly reducing the rehabilitation time and costs for hospitals [2, 5, 12, 14].

Some authors believe that the described technique is superior in efficiency to other local island flap methods, such as V-Y [12]. Compared to the transplantation of free flaps with microvascular anastomoses or perforator propeller flaps on the isolated artery, the presented method undoubtedly wins in terms of time spent in the operating room. According to our data, the average time to complete one case is 67 minutes. The research works of F. Behan et al. [4—6] and J. S. Khouri et al. [12] totally support this trend, although the authors note that the time spent in the operating room may also depend on the size of the defect itself. At the same time, plastic surgery using any other method, when perforator island flaps are used, takes at least 120 minutes. In cases of using the technique of microsurgical anastomoses for the transplantation of free flaps, this time increases occasionally [10, 17]. The relatively simple design and the absence of a directive need for invasive X-ray examinations at the stage of preparation for surgery enable us to recommend the keystone perforator island flap technique for adequate restoration of lost tissues with a complete fasciocutaneous covering with minimal surgical risk for the patient and excellent functional and aesthetic results [5—7, 17].

Other advantages of the described method include: a more stable blood supply with rapid postoperative restoration of perfusion in displaced tissues; minimal damage to the donor zone adjacent to the defect; a functionally and aesthetically acceptable final result of the lost skin restoration with a full-fledged skin-fascial flap; and a good indicator of the cost-effectiveness parameter [7, 8, 17].

Conclusions

The closure of lower limb defects caused by shrapnel and mine-explosive combat injuries with keystone perforator island flaps improves the efficiency of reconstructive surgery. The keystone perforator island flap technique requires basic preoperative preparation of the patient, is easy-to-use, and exhibits a fairly high level of reliability at the same time. In most cases, keystone perforator island flaps provide primary and single-stage closure of a large defect in the thigh, in the area of the knee joint, and lower leg in the absence of secondary defects that are common at donor sites when alternative techniques are chosen. The use of keystone perforator island flaps can be considered a priority technique for plastic closure of deep and extensive lower limb defects in the presence of intact and usable donor tissue resources adjacent to the defect.

Declaration of interests

The authors declare no conflicts of interest.

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Ethics approval and written informed consents statements

All procedures performed in the study and involving human participants were carried out in accordance with the ethical standards of the institutional and/or national research committee, 1964 Helsinki declaration and its later amendments or comparable ethical standards.Written informed consent was obtained from all individual participants included in the study.

Authors contributions

Concept and design of the study: S. V. Sliesarenko; surgery in the clinic: S. V. Sliesarenko, P. A. Badiul, O. I. Rudenko, M. I. Romanshuk; Treatment of patients in the clinic: O. I. Rudenko, M. I. Romanshuk; literature review and discussion of the results P. A. Badiul, O. I. Rudenko, materials and research methods; carrying out research: S. V. Sliesarenko, M. I. Romanshuk.

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Закриття мінно-осколкових бойових дефектів нижніх кінцівок пластикою перфорантними keystone клаптями

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В умовах воєнних дій в Україні питання надання медичної допомоги постраждалим цивільним і військовим є особливо актуальним і гострим. У професійній діяльності пластичних хірургів стоїть завдання відновлення обширних і глибоких ранових дефектів в короткий термін і з високим ступенем відновлення пошкодженого органу, особливо опорної функції. Висвітлено досвід авторів щодо пластичної реконструкції бойових ушкоджень покривів і м'яких тканин нижніх кінцівок за допомогою локальних перфорантних keystone клаптів.

Матеріали та методи. Проведено ретроспективний огляд застосування 49 keystone клаптів у 28 пацієнтів (26 чоловіків і 2 жінки) з кульовими та мінно-осколковими пораненнями, які проходили лікування в клініці у період з 2014 до 2022 р.

Результати. У всіх випадках великі ранові дефекти були повністю закриті одноетапно. Пацієнти виписані з одужанням. При некритичних ускладненнях у 2 (4 %) випадках проведено накладення вторинних швів, що збільшило тривалість лікування на 6 днів. Час роботи в операційній, витрачений на транспозицію одного клаптя, становив від 40 до 95 хв (у середньому — 67 хв).

Висновки. Результати свідчать про високу частоту успішної реконструкції дефектів бойових поранень на нижніх кінцівках за допомогою локальних перфорантних keystone клаптів. Продемонстровано простоту доопераційної підготовки пацієнта і виконання операції та високу надійність запропонованої методики. У більшості випадків перфорантні keystone клапті дають змогу первинно та одномоментно закрити великий дефект на стегні, в ділянці колінного суглоба і гомілки за відсутності вторинних дефектів, характерних для донорських ділянок з вибором альтернативних методик.

Ключові слова: реконструктивна хірургія, перфорантний клапоть, бойове поранення, рани, keystone клапоть.

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