CHAPTER 44

COMPLICATED LOWER EXTREMITY WOUND CLOSURE

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The closure of soft tissue defects presents a challenging dilemma in reconstructive surgery of the lower extremity. Traditionally, local or distal flaps, or skin grafts have closed large wounds, however, over the last few decades, substantial research and development in soft tissue expansion has lead to additional options in the reconstructive surgeon's armamentarium. Primary or delayed primary closure of wounds involves the use of several plastic surgical principles such as undermining and stretching. Presented is a review of the biomechanical properties of skin, as well as current trends in the closure of large wounds utilizing tissue expanders, skin stretching devices, and a recently developed technique of vacuum-assisted wound closure. Finally, the indications, contraindications, and applications of tissue expanders, skin stretching devices and the newly developed vacuum-assisted wound closure in the lower extremity are discussed.

VISCOELASTIC PROPERTIES OF SKIN

Skin constitutes a dynamic biological structure with unique biomechanical properties that have a role in successful skin stretching. The stretch is related to the viscoelastic nature of skin. The following viscoelastic properties of skin allow large defects to be closed without the use of flaps or grafts: inherent extensibility, biologic creep, mechanical creep, and stress relaxation.

Surgeons can visualize the *inherent extensibility* of skin when an excised ellipse of skin is closed primarily. Of course this property varies from one anatomic site to another. The classic pinch test (lifting and folding the skin with one's fingers) can be utilized to estimate the amount of skin that can be excised and still closed primarily.[1] When excising skin with two converging semi-elliptical incisions, the length to width ratio of the skin ellipse is always an important consideration. The most preferred length to width ratio is three to one. This, however, may be unobtainable for different reasons, making the other viscoelastic properties of skin extremely important.

Biologic creep is evident in situations with slowly expanding subcutaneous forces such as tumor, obesity, and the gravid uterus or during the use of subcutaneous tissue expanders. This is not skin stretching, but rather a slow adaptation of tissue. The epidermis responds to expansion with increased mitotic activity in the basal cell layer, but the thickness remains constant. Also noted on histologic examination are thickening of the stratum spinosum and flattening of the rete pegs. The dermis is substantially affected by expansion. The dermis decreases in thickness, however, there are an increased number of fibroblasts, myofibroblasts and bundles of collagen that are formed. The collagen fibers orient themselves parallel to the force of expansion. The subcutaneous fat and muscle do atrophy some. But, probably the most important histologic factor of expanded tissue is the presence of a fibrous capsule that forms around the implant or expanding tissue. The capsule is primarily composed of collagen, fibroblasts and myofibroblasts. The outer capsular layer contains a rich vascular network of newly formed vessels secondary to angiogenesis, which help vascularize the dermis by communicating with the papillary dermal plexus.[2-4]

Another component of skin stretching is its *mechanical creep*. Mechanical creep allows skin to gradually stretch beyond the limits of its normal extensibility.[5,6] When a consistent, constant load is applied to an area of skin, that skin increases in length over time. Gibson et al.[7] studied the behavior of skin under a load, finding that the micro-architecture of dermal collagen is an important inherent property of mechanical creep. Dermal collagen fibers in the relaxed state are normally arranged in a randomly oriented, convoluted pattern. The collagen fibers of the dermis form an intertwined meshwork, which adapts and changes pattern during stretching or relaxing of skin. During stretch, collagen fibers align in the direction of the stretching force. Presuturing and the use of skin stretching devices (Sure Closure™) utilize this property.[1,5] Initially, when skin is stretched it will extend a certain distance with little increased load ("limit strain"). Once the majority of the fibers are rearranged parallel to the line of stretch, very little extension is obtained due to the fibers resisting further extension ("terminal stiffness") (Fig. 1).[7-9]

Finally, the last property that adds to skin viscoelastic nature is *stress relaxation*. This relates closely to mechanical creep. Stress relaxation occurs when skin is stretched a given distance and that distance is held constant; the force required keeping it stretched gradually decreases (Fig. 2).[8]

One of the best ways to take advantage of the previous properties is the concept of *cycle loading*. Cycle loading involves intermittent stretching of skin followed by short periods of relaxation. This process consists of loading the skin for several minutes, followed by a short period of relaxation (about one minute), repeated about three or four times, seems to be the optimal method of cycle loading.[1] Skin stretching devices employ the technique of cycle loading, but it is modified over a longer period of time.

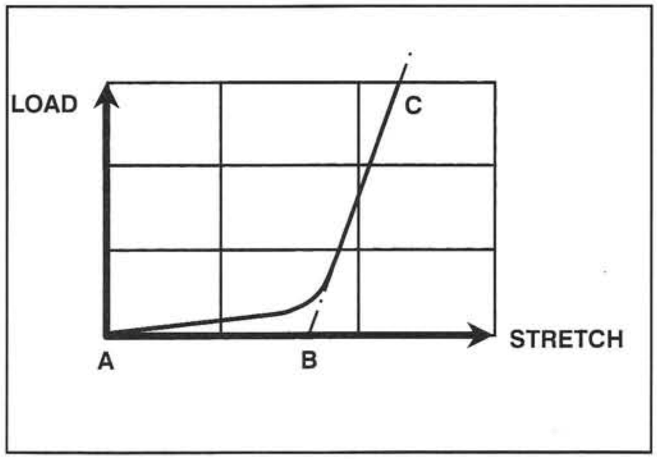

Figure 1. A typical stress-strain curve of human skin. Initially, when skin is stretched the amount of load required is small compared to the gain in length. Thereafter great increases in the load are necessary for further lengthening. AB measures "limit strain," the slope of BC "terminal stiffness."

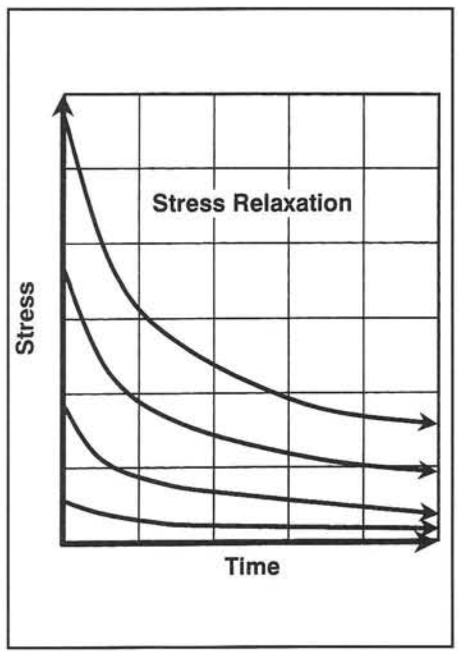

Figure 2. The stress relaxation that occurs in skin increases with the applied load and the amount of force required to keep the skin stretched gradually decreases.

TISSUE EXPANDERS

Tissue expansion has become a widely used adjunct in reconstruction of the skin. Tissue expansion may be used for overcoming tissue shortage, for obtaining skin with desirable qualities, for creation of flaps not otherwise possible, and for minimizing flap donor site problems.[3,10] Neumann[11] in 1957 was the first to describe the use of a subcutaneously placed collapsed rubber balloon in tissue expansion. This allowed him to reconstruct a partially avulsed ear. The use of this technique provided sufficient skin of ideal color, texture and structure to close the defect without creating a secondary defect. Since this first paper, the technique of tissue expansion has been applied at virtually every site in the body. The use of tissue expanders in podiatric surgery was described by Zainer et al.[2] in 1988 for a scar revision over the medial aspect of the ankle.

Historically, Radovan in 1976 utilized the first silastic saline filled temporary tissue expander in the removal of an arm tattoo. This technology was later used in reconstruction of postmastectomy defects. The prototype expander was a silicone gel envelope with a silicone tube leading to a separate port through which saline could be injected, causing expansion of the envelope. Originally two injection ports were needed, one for inflow and one for outflow. However, now a single self-sealing valve is the industry standard. Austad, around the same time developed the concept of a tissue expander filled percutaneously, and later developed an osmotically driven self-expanding implant. Today the industry standard is the Radovan-type expander (with either a silicone main sac connected to a distant injection port via a silicone tube or an integral injection site).[3] There are at least seven different models available in virtually any shape and in any size (1 ml to 1000 ml) (Table 1).[12]

Tissue expander insertion requires three steps. First, the deflated expander is surgically inserted into a subcutaneous pocket created by blunt dissection. Second, sterile saline is injected over a series of office visits after adequate healing time. The injections are usually performed about one to two times per week. Finally, the tissue expander is removed and the expanded skin is used to cover the defect.[2,3]

A primary disadvantage of tissue expansion is the long time required for complete expansion, sometimes up to 12 weeks. One of the reasons for the lengthy expansion time is secondary to the need of overexpanding the skin beyond what is thought necessary, allowing for some elastic return of the skin to its pre-expanded length. The lengthy delay has lead to research in rapid expansion. Sasaki[13] utilized a technique of limited intra-operative tissue expansion. This procedure employs a smaller tissue expander placed under the wound edges. Expansion and deflation are then cycled over a 15 minute period. This is the same concept that skin stretching devices are based on. However, some authors have suggested it is the undermining performed that provides the ultimate gain not the tissue expander.[14] Theoretically, the gains achieved by undermining are not the result of mechanical creep, but is secondary to the mechanical release of the overlying tissue from its anatomic underpinning allowing the surgeon to mobilize the tissue.

In general, avoidance of soft tissue expansion is recommended in extensively scarred areas with compromised blood supply after trauma, vascular disease, osteomyelitis or other conditions that require a well-vascularized flap. Complications secondary to tissue expanders are largely a function of surgical experience, anatomic site, patient selection and speed of inflation. Some reports list an incidence of complications as high as 40%.[3,10,15] However, many authors have succeeded in achieving a much lower complication rate of about 5%.[16,17] These complications can be divided into major and minor complications. Major complications include infection, implant failure, induced tissue ischemia, hematoma and implant exposure. Minor complications include seromas and neuropraxia. Typically, these complications result in a delay of reconstruction and not tissue loss. Complication rates are also very site specific. Regional differences in skin laxity, vascular supply, thickness of subcutaneous tissues and the presence or absence of an additional layer of muscle or fascia contribute to the variability. The head and neck and distal extremities account for a disproportionate number of the complications. This is attributed to body motion, gravitational pooling of the saline, relative thickness of the skin and subcutaneous tissue in the area, and migration of the expander.[3]

Table 1

TISSUE EXPANDERS (SHAPES, SIZES, DIAMETER AND PROJECTION)***

Shapes	Sizes	Diameter (length/width)	Projection
1. Rounds (with remote injection dome)	400-1000cc	11.3 - 15.5cm	5.9-7.8cm
2. Rounds (with integral injection site)	same	same	same
3. Rectangle (with remote injection dome)	50-700cc	6.9 x 3.2 - 15.0 x 8.0cm	3.2 - 7.9cm
4. Rectangle (with integral injection site)	same	same	same
5. Crescents (with remote injection dome)	50-500cc	9.0 x 5.7 19.6 x 12.4cm	2.7-5.5cm
6. Ellipticals* (with remote injection dome)	25-125cc	6.0 x 4.0 15.0 x 5.0cm	2.3-3.3cm
7. ISLE**	2-100cc	2.5 x 1.0 7.0 x 3.5cm	————

* low profile design facilitates placement into tight- skinned areas
** ISLE (Intraoperative Sustained Limited Expansion) temporary only as described by Sasaki[13]
*** Mentor H/S, Inc., 5425 Hollister Ave., Santa Barbara, CA 93111

Vogelin et al.[18] reviewed a series of 34 patients, concluding tissue expansion is a legitimate option in lower limb reconstruction. However, this technique was only successful in 23 patients (67.6%) and 44% of the 34 patients had minor wound healing problems. In the eleven patients whose ultimate goal of surgery was not met, five patients were successfully treated with another surgical modality. Considering that a larger percentage of complications arise when utilizing tissue expanders on the lower extremity, the authors recommend exhausting all other possible treatment modalities prior to selecting this type of therapy. If tissue expansion is deemed necessary, then the patient should be counseled on the possible complications and postoperative course. A compliant patient is essential for lower limb reconstruction with tissue expansion.

SKIN STRETCHING DEVICES

Skin stretching devices take advantage of the previously noted properties of mechanical creep, stress relaxation and cycle loading. Several devices are available that take advantage of the viscoelastic properties of skin (Table 2). The first device was designed by Hirshowitz in 1993.[6] The device (Sure Closure™) utilizes the previous properties and incremental traction to approximate wound edges. Its indications include wound closure when skin retraction or deficit presents a major problem in gaining edge to edge apposition, or in mobilizing wound edges over poorly vascularized deep structures, such as bone. The Sure Closure™ device was shown to be more efficient and cost effective in closing complex wounds, compared to conventional wound closure methods (flaps and grafts).[19] Some clinical applications of skin stretching devices include closure of open fasciotomies performed for acute compartment syndrome, closure of amputation stump wounds, wounds involving exposed bone, joint, plates and screws, wound closure after open fracture and for overcoming tissue shortage or scar revision.[5,6,20]

The (Sure Closure™) device is designed for the intradermal placement of two long pins (not greater than 5mm from the wound edges) which are engaged by hooks on the arms of the skin stretching device. A threaded screw passes through the center of the arms allowing tension to be applied between the two wound edges when the screw is tightened (Figs. 3A-3C, 4A-4D). The stretching force is spread over a wide area, thus preventing local areas of damage secondary to the individual hooks. No undermining is performed in using the skin stretching devices. This is because the trauma undermining imparts may effect the viability of the newly stretched integument.

The device may be applied preoperatively, intraoperatively or postoperatively under sterile conditions. Hirshowitz et al.[6] advise 20 to 30 minute intraoperative application, as a general rule, for most wounds with normal skin and subcutaneous tissues. However, in chronic wounds the time required for stretching is prolonged. This is thought to be secondary to fibrosis and edema along the skin margins. The device may be used up to three days in these instances either preoperatively or postoperatively. If used at bedside, local anesthesia may not eliminate pain completely if the device is overtensioned. Pain may help in the judgement of the amount of tension applied to the wound.

Table 2

SKIN STRETCHING DEVICES

Sure Closure™
Zimmer Inc.
PO Box 708
Warshaw, IN 46581

Proxiderm™
Progressive Surgical Products, Inc.
694 Main St.
Westbury, NY 11590

The Proxiderm skin stretching system™ is another device that has been utilized in the management of problematic wounds (Fig. 5). This particular device was studied in the treatment of chronic neuropathic wounds.[21] This device consists of tissue hooks that are inserted into healthy tissue near opposing wound margins. A constant, sustained, low-grade force (approximately 460g) is applied to the margins of the wound. This slowly stretches the wound with full thickness skin. This process may take days to weeks. In this application, healing occurs secondarily. Constant force over a period of days to weeks encourages angiogenesis and tissue generation. The low-grade force applied to the wound (about 5 times less

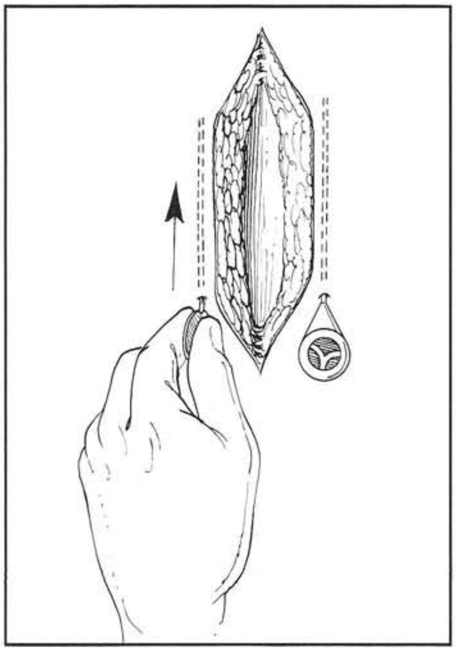

Figure 3A. Application of the Sure closure skin stretching device. The needles are inserted intradermally opposite each other along the intact margins of the wound.

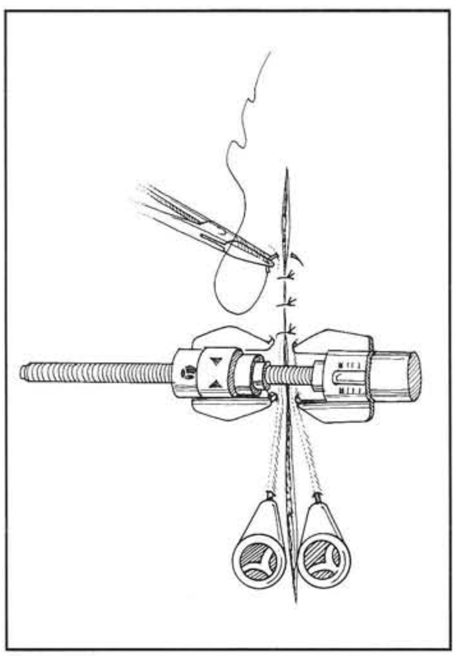

Figure 3C. Wound margins approximated for closure.

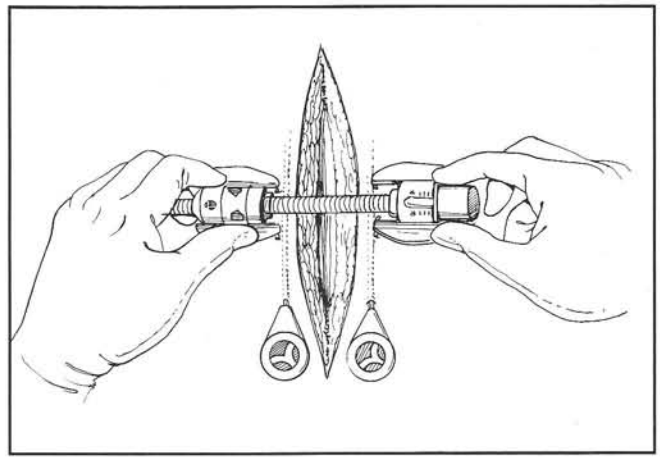

Figure 3B. The Sure Closure device is engaged over the wound.

Figure 4A. The initial wound following excision of a skin mass.

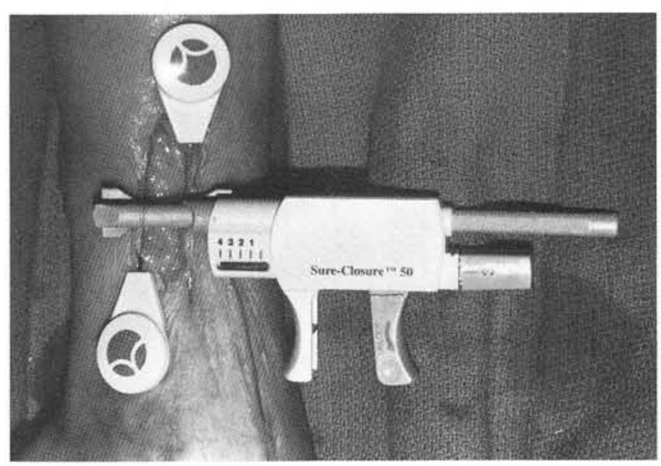

Figure 4B. Application of the Sure Closure skin stretching system™ prior to skin stretching.

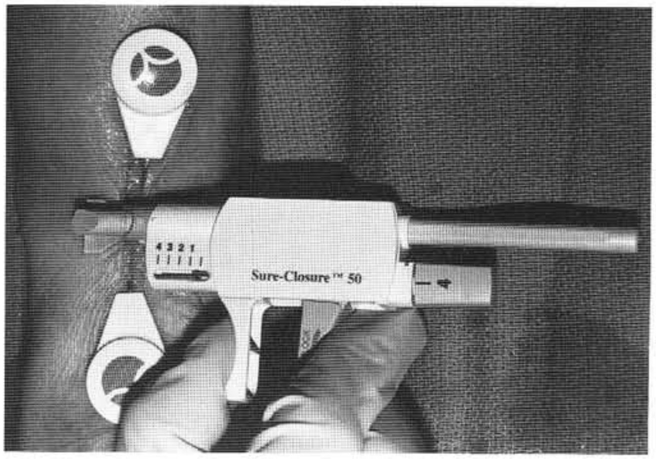

Figure 4C. The wound during skin stretching.

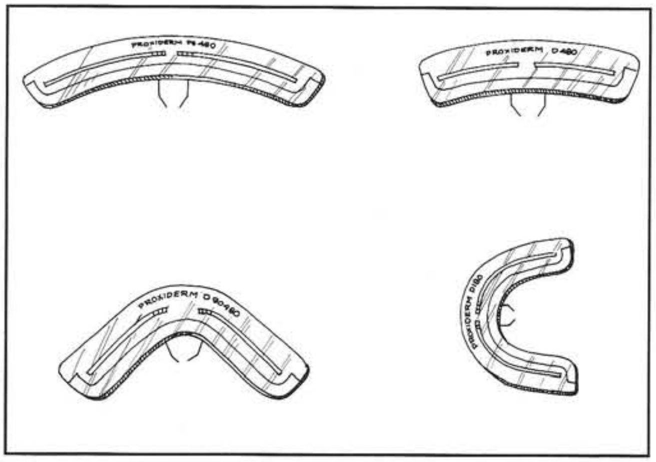

Figure 5. Examples of the Proxiderm skin stretching system(TM).

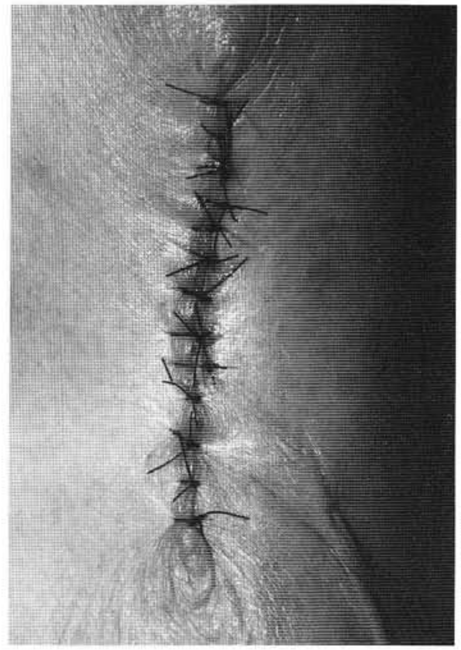

Figure 4D. The wound following skin closure.

than the load applied by Sure Closure™) allows gradual wound closure, reducing the chance of ischemia. Additionally, because of the longer hooks of the device, it is able to close deeper wounds rather than at the skin edge only. The device is also able to accommodate curved surfaces such as the heel. The Proxiderm skin stretching system™ is indicated for chronic wounds that will not heal, or heal by secondary intention in areas where this is sub-optimal. The device does require non-weight bearing and is contraindicated in cases where active inflammation and ischemia are present.[21]

Other skin stretching devices are available however, the same goal of wound closure may be accomplished by other means, such as, using towel clamps or stainless steel suture tensioned over time. In a study by Lam et al.[22] three different wound closure modalities (linear load cycling, balloon expansion, and undermining) were analyzed. The study was performed on the flanks of pigs. All three modalities were deemed effective, but the linear load cycling was shown to be more effective than balloon expansion and undermining in lowering the tension required in closing surgically created defects.

Skin stretching devices are contraindicated when non-viable or atrophic tissue is present at or near the wound edges, when any sign of active infection is present, when previous radiation therapy has been given in the wound area, or the patient is receiving chemotherapy. It is also mandatory to maintain 7mm of separation from the device and underlying neurovascular structures. Potential adverse effects as with any difficult wound closure may include hypertrophic scars, wound dehiscence, incomplete wound closure or traction necrosis.[5,6]

VACUUM ASSISTED WOUND CLOSURE

Recently, a new technique to expedite wound healing using sub-atmospheric pressure (125mmHg below ambient) has been developed.[23,24] The technique was developed as a method to expedite the rate of healing by secondary intention, particularly in compromised and debilitated patients. The method entails placing an open-cell polyurethane foam into the wound, sealing the site with an adhesive tape and applying the sub-atmospheric pressure in a controlled manner with The V.A.C™. The V.A.C is marketed by Kinetic Concepts, Inc. (KCI, San Antonio, TX). The sub-atmospheric pressure applies a uniform controlled force to the inner surface of the wound.

The open-cell foam dressing ensures the equal distribution of the applied sub-atmospheric pressure to all surfaces of the wound in contact with the foam. The foam dressing is cut to the correct size of the wound and then placed inside the wound. The wound site is then covered with an adhesive tape to 5 cm over the adjacent intact skin, which converts an open wound into a controlled closed wound. An evacuation tube exits the foam dressing and runs to a canister, which collects effluent fluid. The canister is in turn connected to the vacuum pump. The magnitude of sub-atmospheric pressure applied by vacuum pump is adjustable. The pump may be used in a continuous or intermittent manner. Dressings are usually changed at 48-hour intervals under clean conditions, not necessarily sterile.[23,24]

This device has been used on chronic wounds (pressure ulcers, stasis ulcers), subacute wounds (infection and dehiscence, avulsions and open amputations), acute wounds (trauma) and after split-thickness skin grafts with excellent success. Argenta et al.[24] found success utilizing The V.A.C™ in 296 of 300 patients. The wounds were treated until they were completely closed or covered with split thickness skin grafts or local flaps. Elimination of nonviable tissue is paramount in the success of this device. Nonviable tissue can become a focus for bacterial proliferation, which impedes wound healing.

Research performed on pig models suggest using The V.A.C™ leads to increased blood flow levels, increased granulation tissue formation, increased survival of later random-pattern flaps and decreased tissue bacterial count. The theory behind the increase in localized blood flow following application of sub-atmospheric pressure is due to the active removal of the excess interstitial fluid (third space fluid) from the tissues surrounding the wound, which leads to a dilation of the arterioles (restoring blood flow) secondary to decompression. The highly significant increase in the rate of granulation tissue formation is thought to be due to the uniform force applied to the wound margins which recruit the tissue's visco-elastic nature and stimulates new granulation tissue. This employs the same type of mechanical stress theories as soft-tissue expanders and skin stretching devices. As noted previously, the mechanical stress applied to the wound can lead to angiogenesis and increased mitotic activity. The decreased bacterial count is correlated to the increased oxygen levels in the wound. The increased oxygen available makes neutrophils more effective and it also reduces the chance of anaerobic infection. All of the above postulated mechanisms of The V.A.C.™ are supported by the better survival of random-pattern flaps following the use of this device.[23]

Complications encountered using this therapy have been relatively few. Some complications have arisen from pressure sores created by the evacuation tube on the skin exiting the bandage. Some patients with chronic wounds have pain complaints with the use of the device. Excessive ingrowth of granulation tissue into the foam dressing has occurred in patients when the dressing change has been delayed, or in young healthy patients with acute wounds. Occasionally, odor may become a problem in chronic wounds during treatment.[23,24]

CONCLUSION

Soft tissue expansion or skin stretching may be used for overcoming a shortage of tissue, for obtaining skin with desirable qualities, for creation of flaps not otherwise possible and for minimizing flap donor site problems. This paper summarizes the viscoelastic properties of skin and presents a review of new mechanically assisted methods of wound closure. These devices are not a panacea, but they do provide the reconstructive surgeon another option in the treatment of complex wounds, which may prove to be a valuable asset to the foot and ankle surgeon.

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