

Journal of Rehabilitation Research and Development Vol. 39 No. 4, July/August 2002 Pages ?-?

Development of a mechanical device to replace medicinal leech (*Hirudo medicinalis*) for treatment of venous congestion

Michael L. Conforti, DVM, MS; Nadine P. Connor, PhD; Dennis M. Heisey, PhD; Ray Vanderby, PhD; David Kunz, PhD; Gregory K. Hartig, MD

Department of Research, William S. Middleton VA Hospital, Madison, WI; Department of Surgery, University of Wisconsin Medical School, Madison, WI

Abstract-Medicinal leeches are used to treat venous congestion, a complication of reconstructive surgery. Despite substantial drawbacks of leeching, little progress has been made to develop a device that would replace the leech for this purpose. The goal of this study was to develop and test mechanical prototypes for the treatment of venous congestion. We tested four prototypes (1, 2, 3a, and 3b) using congested fasciocutaneous flaps in swine. Blood removed by each prototype was measured for up to 4 hours. On average, the four prototypes removed 609%, 644%, 853%, and 811% more blood, respectively, from congested flaps versus a leech. Prototypes 3a and 3b, which allowed for innovative subcutaneous chemical (3a and 3b) and mechanical (3b) anticoagulation at the bleeding wound, sustained high levels of blood removal for up to 4 hours. Thus, a mechanical device can potentially replace the use of leeches for treating venous congestion.

Key words: Hirudo medicinalis, *mechanical device, medicinal leech, reconstruction, replantation, venous congestion.*

INTRODUCTION

Reconstructive surgical procedures, such as free flaps, pedicle flaps, and replantation of amputated tissues, often include an anastomosis between either surgically ligated or traumatically severed blood vessels. Venous congestion is a serious complication of these types of procedures and occurs when the venous outflow from a tissue is reduced relative to arterial input. Kinking or impingement on the veins and/or thrombus formation within the veins can cause this reduction [1–4]. If venous congestion is not corrected (either surgically or via some other means), the developed stasis within the vasculature of the tissue will cause the replanted region to necrose.

Although medicinal leeches (*Hirudo medicinalis*) have been a part of medical practice for thousands of years, not until the advent of reconstructive microsurgery in the 1960s did bloodletting by the leech have a legitimate medical purpose. Specifically, medicinal leeches are placed upon the congested tissue to facilitate removal of excess blood until microvenous circulation can be effectively reestablished approximately 4 to 10 days after surgery [5–11]. Unfortunately, leeches only remove small quantities of blood from the congested tissue and cannot be relied upon to effectively decongest large regions of tissue. In addition, the use of leeches is

This material was based on work supported by a Rehabilitation Research and Development grant from the Department of Veterans Affairs.

Address all correspondence and requests for reprints to Michael L. Conforti, DVM, MS, William S. Middleton VA Hospital, Department of Research, 2500 Overlook Terrace, Madison, WI 53705.

suboptimal because of other drawbacks [12]. These drawbacks are substantial and include negative patient and family perception, unreliability of leech attachment (i.e., the leeches may not attach to, or may migrate from, the impaired tissue and may feed on healthy adjacent skin), excessive cost because of constant staff monitoring, and the possibility of infection [13–16].

There have been several attempts in the last 10 years to develop a mechanical and/or chemical leech that would replace the medicinal leech [17–20]. Although these attempts showed some success, a clinically applicable product has not been developed to date, which would replace the use of medicinal leeches for the successful treatment of venous congestion.

The specific goal of this study was to begin prototype development and testing of a mechanical device to replace the medicinal leech. Ultimately, the mechanical device will be optimized for minimum skin surface (cosmetic) and underlying tissue damage, maximum therapeutic bleeding time, and maximum therapeutic blood removal. Our first generation prototypes described in this study begin the testing and manipulation of functional concepts for device optimization. A swine model was chosen over a small animal model to maximize the clinical relevance of this study. Swine have cutaneous morphology similar to humans and a large blood supply, preventing the possibility of fatal exsanguination during treatment [21–22].

METHODS

Eleven mixed-breed pigs, weighing 20.5 kg to 24.2 kg were preanesthetized with intramuscular xylazine (2 mg/kg), Telazol (6 mg/kg), and atropine (1 mL). The animals were mechanically ventilated with 100 percent 0_2 and isoflurane (1.5 to 2.5 percent). Isotonic fluids were administered intravenously (IV) throughout the experiment (10 mL/kg/h). Blood pressure and rectal temperature were monitored.

Model of Venous Congestion

A 9- \times 9-cm cutaneous pedicle flap based on the superficial circumflex iliac artery and venae comitantes (VCs) was elevated, one per animal, as described previously [12,23]. The right or left flank was used based on a predetermined random schedule. The VCS were completely occluded with the use of vascular clamps; after which, the artery was treated with 0.1 mL of topical

lidocaine (4 percent) to prevent and/or treat vascular spasm. A thin cloth was placed under the flap to isolate it from the surrounding tissue. Before any surgical manipulation and after the VCs were clamped, laser Doppler images were taken to verify venous stasis.

Mechanical Device Prototypes

All prototypes consisted of a hand-blown glass shell (approximately 1.5 cm in diameter) that was adhered to the skin over a bleeding wound with veterinary-grade adhesive (Nexaband). Each shell had inflow and outflow ports that allowed suction, anticoagulation, and air intake into the glass shell. Full schematics of prototypes 1 to 3 are shown in **Figure 1**. Prototype 3 had two slightly different variants, denoted as 3a and 3b. In total, six functional concepts were integrated into the design of these prototypes, as described in the following paragraphs. Parameters of concepts 1, 5, and 6 were varied across prototypes. A summary of the variations among the prototypes is found in the **Table**.

Prototype 1

- Concept 1 is a surgically created bleeding wound. A punch biopsy was used to excise an 8-mm diameter area of skin extending through the epidermis and dermis.
- Concept 2 is suction. Computer-controlled constant suction at -50 to -70 mmHg (Labview, National Instruments).
- Concept 3 is surface chemical anticoagulation via irrigation. Dilute heparinized (10 U/mL), isotonic saline was dripped directly onto the bleeding wound via an internal glass capillary tube at a rate of 200 to 500 mL/h.
- Concept 4 is surface mechanical anticoagulation via irrigant turbulence. The suction that was applied to the shell drew in room air via a 22-gauge hypodermic needle or similar internal diameter (ID) polyethylene tube inserted though a port in the glass shell. This caused turbulence (bubbles) in the blood-irrigant mixture pooled at the skin surface within the shell and created mechanical anticoagulation at the incision surfaces.
- Concept 5 is subcutaneous chemical anticoagulation via injection or infusion. Six bolus intradermal injections (0.2 mL each) of concentrated heparin (1,000 U/mL, Elkins-Sims) were given (three equidistant injections within 5 mm to 8 mm of the proposed wound just

CONFORTI et al. Device for treating venous congestion



Figure 1.

Schematics of prototypes. (a) Prototype 1 used a punch biopsy bleeding wound alone. (b) Prototype 2 used crossed stab incisions with undermining and continuous subcutaneous infusion of concentrated heparinized saline surrounding wound. (c) Prototypes 3a and 3b used crossed stab incisions with undermining and continuous slow release of concentrated heparinized saline in bleeding wound via a hydrogel impregnated microporous polyethylene disk. Circled numbers indicate concepts described in text that were integrated into prototype design. PE = polyethylene.

Table.

Summary of prototype variations. Surgically created bleeding wound, subcutaneous chemical anticoagulation, and subcutaneous mechanical anticoagulation (concepts 1, 5, and 6, respectively) were varied among mechanical prototypes. Suction, surface chemical anticoagulation, and surface mechanical anticoagulation (concepts 2 to 4) were constant among four prototypes. N/A = not applicable for that particular prototype.

Prototype	Trials (n)	Test Duration (h)	Concept 1	Concept 5	Concept 6
			Wound	SubQ Chemical (Heparin) Anticoagulation	SubQ Mechanical Anticoagulation
1	2	3	Punch biopsy	Bolus injections	N/A
2	2	3	Crossed stab incisions	Bolus injections plus continuous infusion at injection sites	N/A
3a	4	4	Crossed stab incisions	Bolus injections plus continuous infusion into wound via hydrogel disk	N/A
3b	5	4	Crossed stab incisions	Bolus injections plus continuous infusion into wound via hydrogel disk	Manual disk rotation

before wound creation and three equidistant injections at sites 15 mm from the glass shell immediately after device attachment).

Concept 6 is subcutaneous mechanical anticoagula-

tion via disk agitation. Not applicable.

Prototype 2

• Concept 1 is a surgically created bleeding wound. Two crossed stab incisions, each 8 mm in length, were made through the epidermis and dermis. An 8-mm to 10-mm diameter area (centered on the crossed stab

incisions) was undermined with a 3.2-mm angled ophthalmic slit knife (Alcon, Inc.). This undermining occurred between the dermal and hypodermal layers.

- Concept 2 is suction. Same as prototype 1.
- Concept 3 is surface chemical anticoagulation via irrigation. Same as prototype 1 except a similar ID polyethylene tube, inserted through a port in the glass shell, replaced the glass capillary tube.
- Concept 4 is surface mechanical anticoagulation via irrigant turbulence. Same as prototype 1.
- Concept 5 is subcutaneous chemical anticoagulation via injection or infusion. Same as prototype 1 with the addition of a continuous injection of concentrated heparin (1,000 U/mL/h, Elkins-Sims) at the three sites located 5 mm to 8 mm from the center of the wound.
- Concept 6 is subcutaneous mechanical anticoagulation via disk agitation. Not applicable.

Prototypes 3a and 3b

- Concept 1 is a surgically created bleeding wound. Same as prototype 2.
- Concept 2 is suction. Same as prototypes 1 and 2.
- Concept 3 is surface chemical anticoagulation via irrigation. Same as prototypes 1 and 2, except a 20-gauge hypodermic needle, inserted through a port in the glass shell, replaced the glass capillary tube.
- Concept 4 is surface mechanical anticoagulation via irrigant turbulence. Same as prototypes 1 and 2.
- Concept 5 is subcutaneous chemical anticoagulation via injection or infusion. Same as prototype 1 with the addition of continuous infusion of concentrated heparin (1,000 U/mL/h, Elkins-Sims) into a hydrogel-impregnated microporous polyethylene disk (8 mm wide × 2.5 mm high, Porex, Inc.), which had been inserted subcutaneously into the stab incisions during device attachment. The heparin was delivered to the disk via a polyethylene tube (prototype 3a) or stainless steel 15-gauge hypodermic tube (prototype 3b) inserted through a port in the shell. The disk and tubing were bonded with urethane adhesive.
- Concept 6 is subcutaneous mechanical anticoagulation via disk agitation (3b only). The stainless steel hypodermic tubing attached to the subcutaneous disk was manually turned 90° every 10 to 20 minutes, thus rotating the disk.

The hydrogel that impregnated the microporous disk consisted of 10 percent polyvinyl alcohol (hot soluble), 5 percent MgCl₂, 0.5 percent glutaraldehyde (50 percent), 3 percent formaldehyde (37 percent), 4 percent glycerol, and 2 percent sodium heparin mixed in sterile water (adapted from Goosen, 1983) [24]. The microporous disk was impregnated with 0.5 mL of hydrogel under negative pressure. Sigma Aldrich manufactured all chemicals.

Experiment Protocol

The flap was allowed to congest for 15 minutes after clamping the veins. One mechanical prototype was then adhered to the skin flap over the prototype-specific bleeding wound. The mechanical prototypes were developed and tested sequentially. When testing prototype 3b, we placed two prototypes on the congested flap of two of the animals, bringing the overall sample size to 13 prototype trials.

For each experiment, the blood-irrigant mixture removed by the prototype was collected in 1-hour aliquots over a period of at least 3 hours. We measured the blood volume in each aliquot using methods described in detail in a prior report [25]. Briefly, the red blood cell count (RBCC) per milliliter in a 1-hour blood-irrigant aliquot was multiplied by the number of milliliters in the aliquot. This product equaled the total number of RBCCs in the aliquot, which was divided by the RBCC per milliliter in an IV blood sample to give the blood volume in each hourly aliquot in milliliters. Blood volumes removed by the mechanical devices were compared to medicinal leech standards previously documented under identical conditions (i.e., 4.7 mL over 3 hours) [12]. Percent increase in blood removed over a 3-hour period using the mechanical prototypes was calculated relative to the values of blood loss during leech therapy. We performed statistical analysis using independent t-tests ($\alpha = 0.05$).

In two separate representative experiments (one treatment and one control), similar but smaller $6\text{-cm} \times 7\text{-cm}$ flaps were congested as previously described in this paper. One flap was left untreated and one flap was treated with prototype 3b. The treatment and control periods of complete venous obstruction were 4 hours. The amount of decongestion or congestion that developed over the 4-hour experimentation period was documented via digital photography.

RESULTS

The combined mean increase in blood removed for all prototypes (n = 13 trials) as compared to blood removed by medicinal leeches over a 3-hour period was 759 percent. As shown in **Figure 2**, prototypes 3a and 3b removed significantly more blood over a 3-hour period than the average medicinal leech under identical conditions [12]. Blood volumes removed by prototypes 1 and 2 dropped substantially after the first hour. In contrast, blood removal by prototypes 3a and 3b was relatively stable across time (**Figure 3**).

Figure 4 contains images of an untreated control flap and a treated flap using prototype 3b after 4 hours of complete venous obstruction. As suggested by these images, prototype 3b allowed stable decongestion of the entire flap across time, evidenced by the minimal color difference between the flap and surrounding normal skin. Without treatment, the color of the control flap progressively darkened, as observed by the very dusky, deep purple when compared to the surrounding normal skin.

DISCUSSION

Venous congestion is a serious complication of reconstructive surgery. Given the many drawbacks of medicinal leech therapy, the use of leeches to alleviate



Figure 2.

Mean blood volume removed over a 3-h period for medicinal leech versus each prototype. In a prior study, mean blood volume removed by medicinal leech was 4.7 mL [12]. Blood volumes removed by prototypes 1, 2, 3a, and 3b constituted increases of 609%, 644%, 853%, and 811% relative to average medicinal leech. Error bars represent standard deviations. $*p \le 0.05$.



CONFORTI et al. Device for treating venous congestion

Figure 3.

Blood volume removed versus treatment method after 4 hours of complete venous obstruction. Prototypes 1 and 2 had a precipitous decrease in blood volume removed (59.8% and 54.7%, respectively) between first and second hour. In contrast, prototypes 3a and 3b sustained the amount of blood removed over a 4-h period.

venous congestion only compounds an extremely difficult clinical situation. The four prototypes developed and tested in our laboratory exceeded the capability of the medicinal leech (*Hirudo medicinalis*) in removing blood from a clinically relevant congested flap model. The most effective prototypes (3a and 3b) sustained relatively stable bleeding rates for at least 4 hours. Furthermore, these prototypes do not possess the negative characteristics of live leech use.

In this study, the device concepts and concept manipulations were used to advance the long-term goals of minimizing skin surface (cosmetic) and underlying subcutaneous tissue destruction, maximizing therapeutic bleeding time, and maximizing therapeutic blood removal. The crossed stab incisions (concept 1, prototypes 2, 3a, and 3b) were less destructive and more easily repaired with respect to the skin surface versus the excisional punch biopsy used in prototype 1. By undermining between the dermal and hypodermal layers (8-mm to 10-mm diameter area), we presumably were able to tap into a greater number of large cutaneous vessels located between these layers. Thus, undermining created increased bleeding surface area without the excision of overlying skin.

Suction strength (concept 2, all prototypes) was chosen based on the prior observation that increased suction caused increased tissue damage (visible bruising) of the skin surface under the device. Blood vessel rupture and



Figure 4.

Representative images of (a) untreated and (b) treated 6-cm \times 7-cm fasciocutaneous flaps. (a) Control flap, 4 h after clamping veins. (b) Treatment flap completely decongested with use of prototype 3b, 4 hours after clamping veins (3.5 h of treatment).

destruction (bruising) within the dermal and epidermal layers could possibly decrease bleeding time and volume. The use of chemical and mechanical anticoagulation of the skin surface via irrigation and turbulence (concepts 3 and 4, all prototypes) prevented obstructive clot formation on the skin surface that would impede the exit of blood from the wound.

Heparinization of the flap via six bolus injections of heparin (concept 5, all prototypes) most likely minimized thrombosis formation within the flap. The extent of this minimization needs to be studied further to determine the optimal use of heparin in areas distant to the actual device application site. The hydrogel and microporous polyethylene disk (concept 5, prototypes 3a and 3b) allowed for innovative subcutaneous anticoagulation (chemical and mechanical). The slow release of heparin at the bleeding edge of the wound via the disk presumably created a heparinized subcutaneous microenvironment. This microenvironment was more effective at sustaining bleeding than continuously injecting heparin at three sites 5 mm to 8 mm from the wound center (prototype 2). Furthermore, the combination of heparin infusion into the disk and disk rotation (concept 6, prototype 3b) was the best modality for sustaining bleeding past 3 hours, most likely because of the added disruption of subcutaneous clot formation. Optimization of heparin

concentration for disk infusion and optimization of disk rotation timing will be studied in future studies.

The amount of decongestion obtained by treating a congested flap with prototype 3b was encouraging, in that an entire 6-cm \times 7-cm (42-cm²) flap was visually decongested after 4 hours of complete venous obstruction. In comparison, the maximum skin surface area decongested by a medicinal leech was a 1.6-cm diameter area (4-cm²) under identical conditions, when evaluated via laser Doppler imaging and visual assessment of improvements in skin color [12]. Furthermore, maximal decongestion by a medicinal leech was short-lived, occurring during the latter half of active feeding (~30 to 40 minutes) and the first hour of passive bleeding after the leech detached.^{*}

In summary, prototype 3b demonstrated excellent potential to replace the use of medicinal leeches for the treatment of surgically uncorrectable venous congestion. Extended protocols to study the efficacy of prototype 3b for the successful treatment of congested fasciocutaneous flaps in swine will be the next stage in developing a medicinal leech replacement. Through further concept optimization, testing, and clinical trials, we are confident

^{*}Unpublished observations, Conforti ML, 2000.

CONFORTI et al. Device for treating venous congestion

that a commercially viable medical device can be produced in approximately 2 to 3 years.

The development of a mechanical device for the treatment of venous congestion appears critical, especially considering the many drawbacks of medicinal leech therapy and the recent advancements in microsurgery that involve replantation and transplantation of large regions of tissues, including entire hands [26,27]. The development of such a medical device would have significant societal benefits. Namely, the psychological trauma and limited effectiveness of medicinal leech use would be overcome in modern medicine.

CONCLUSION

Four mechanical device prototypes were developed and tested for the removal of excess blood from congested fasciocutaneous flaps. The two prototypes that used an innovative subcutaneous anticoagulation technique removed significantly larger blood volumes, relative to the medicinal leech. Furthermore, we were able successfully to decongest a $6- \times 7$ -cm fasciocutaneous flap using the most effective prototype over a 4-hour period of complete venous obstruction. These findings are encouraging with respect to the development of a mechanical device to replace the medicinal leech for the treatment of venous congestion.

REFERENCES

- 1. Jones NF, Johnson JT, Shestak KC, Myers EN, Swartz WM. Microsurgical reconstruction of the head and neck: Interdisciplinary collaboration between head and neck surgeons and plastic surgeons in 305 cases. Ann Plast Surg 1996;36:37–43.
- 2. Khouri RK, Cooley BC, Kunselman AR, Landis JR, Yeramian P, Ingram D, Natarajan N, Benes CO, Wallemark C. A prospective study of microvascular freeflap surgery and outcome. Plast Reconstr Surg 1997; 102(3):711–21.
- Kroll SS, Schusterman MA, Reece GP, Miller MJ, Evans GR, Robb GL, Baldwin BJ. Choice of flap and incidence of free flap success. Plast Reconstr Surg 1995;98:459–63.
- 4. Schusterman MA, Miller MJ, Reece GP, Kroll SS, Marchi M, Goepfert H. A single center's experience with 308 free flaps for the repair of head and neck cancer defects. Plast Reconstr Surg 1994;93:472–78.

- Hayden RF, Phillips JG, McLear PW. Leeches. Objective monitoring of altered perfusion in congested flaps. Arch Otolaryngol Head Neck Surg 1988;114(12):1395–99.
- 6. Smoot EC, Debs N, Banducci D, Poole M, Roth A. Leech therapy and bleeding wound techniques to relieve venous congestion. J Reconstr Microsurg 1990;6(3):245–50.
- Lee C, Mehran RJ, Lessard ML, Kerrigan CL. Controlled trial in venous compromised rat epigastric flaps. Br J Plast Surg 1993;45(3):2356–58.
- 8. Soucacos PN, Beris AE, Malizons KN, Kabani CT, Pakos S. The use of medicinal leeches, *Hirudo medicinalis*, to restore venous circulation in trauma and reconstructive microsurgery. Int Angiol 1994;13(3):251–58.
- 9. Rao P, Bailie FB, Bailey BN. Leechmania in microsurgery. Practitioner 1985;229:901–5.
- Cottler PS, Gampper TJ, Rodeheaver GT, Skalak TC. Evaluation of clinically applicable exsanguination treatments to alleviate venous congestion in an animal skin flap model. Wound Repair Regen 1999;7(3):187–95.
- Foucher G, Henderson HR, Maneau M, Merle M, Braun FM. Distal digital replantation: One of the best indications for microsurgery. Int J Microsurg 1981;3:263–70.
- 12. Conforti ML, Connor NP, Heisey DM, Hartig GK. Evaluation of performance characteristics of the medicinal leech (*Hirudo Medicinalis*) for the treatment of venous congestion. Plast Reconstr Surg 2002;109(1):228–35.
- Lineaweaver WC. Aeromonas hydrophilia infections following clinical use of medicinal leeches: A review of published cases. Blood Coagul Fibrinolysis 1991;2(1):201–3.
- de Chalain TM. Exploring the use of the medicinal leech: A clinical risk-benefit analysis. J Reconstr Microsurg 1996; 12(3):165–72.
- Lancellot M. Relying on past science: Nursing implications of medicinal leech therapy. Medsurg Nurs 1993;2(2): 128–30.
- Varghese MR, Farr RW, Wax MK, Chafin BJ, Owens RM. Vibrio fluvialis wound infection associated with medicinal leech therapy. Clin Infect Dis 1996;22(4):709–10.
- Barnett GR, Taylor GI, Mutimer KL. The "chemical leech": Intra-replant subcutaneous heparin as an alternative to venous anastomosis. Report of three cases. Br J Plast Surg 1989;42(5):556–58.
- Hartrampf CR, Drazan L, Noel RT. A mechanical leech for transverse rectus abdominis musculocutaneous flaps. Ann Plast Surg 1993;31(2):103–5.
- Smoot EC, Ruiz-Inchaustegui JA, Roth AC. Mechanical leech therapy to relieve venous congestion. J Reconstr Microsurg 1995;11:51–55.
- Cottler PS. Development of a skin flap therapy device for interventional fluid transport [unpublished dissertation]. Charlottesville (VA): University of Virginia; 2000; p. 1–186.

- Forbes PD. Vascular supply of the skin and hair in swine. In: Montagna W, Dodson RL, editors. Advances in biology of the skin. New York (NY): Pergamon; 1969; vol. 9.
- 22. Kerrigan CL. The pig as an experimental animal in plastic surgery research for study of skin flaps, myocutaneous flaps, and fasciocutaneous flaps. Lab Anim Sci 1986; 36(4):408–12.
- 23. Arnold F, He CF, Jia CY, Cherry GW. Perfusion imaging of skin island flap blood flow by a scanning laser-Doppler technique. Br J Plast Surg 1995;48:280–87.
- 24. Goosen MFA, Sefton MV. Properties of a heparinpoly(vinyl alcohol) hydrogel coating. J Biomed Mater Res 1983;17:359–73.
- 25. Connor NP, Conforti ML, Heisey DM, Vanderby R, Kunz D, Hartig GK. Augmented blood removal after medicinal leech feeding in congested tissue flaps. J Rehabil Res Dev 2002;39(4):XXX–XXX.
- 26. Troum S, Floyd WE. Upper extremity replantation at regional medical center: a six-year review. Am Surg 1995;61(9):836–40.
- Jones JW, Gruber SA, Barker JH, Breidenbach WC. Successful hand transplantation—one-year follow-up. N Engl J Med 2000;343(7):468–73.

Submitted and accepted for publication June 22, 2001.