A PROPOSED TECHNIQUE FOR THE POSTOPERATIVE MONITORING OF SKIN TENSION IN BELOW-KNEE AMPUTEES

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INTRODUCTION

The presence of abnormal amounts of fluid within body tissues (defined as edema) is generally considered detrimental to normal cell physiology, including wound healing following surgery. Appropriate postoperative wound management seeks to prevent, control and reduce edema.

The accurate monitoring of volume changes within a given mass of tissue can indicate the amount of edema present and thus reflect the effectiveness of the wound management utilized. Unfortunately, volume measurement is technically difficult in the clinical setting. The need to maintain wound sterility, wound support, and control of pain, and the limited efficiency and precision of present monitoring devices, all create technical obstacles. Displacement

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studies using gases or liquids are cumbersome and can violate the sterile wound environment. A comparative study of tissue weight is also impractical, as are photographic, densometric, ultrasonic and radiographic (computerized axial tomography) systems.

This paper proposes a relatively simple technique for measurement of skin tension substantially at right angles to the suture line in a recent below-knee amputation limb. With this technique it is possible to monitor, at least by inference, the changes in pressure within the limb (and the presumed increase or reduction of edema) with various forms of treatment.

While an exacting qualitative readout is impractical at this time, it seems worthwhile to strive for a continuous readout indicative of edema. In our approach we have made numerous assumptions and generalizations about skin, tissue responses, edema formation, and both internal and external forces applied to the residual limb. Even with these obvious potential errors, it is felt that the readout we obtain will reflect, with adequate accuracy, changes in the degree of edema of the residual limb during treatment.

BACKGROUND

For a number of years, Prosthetics Research Study has been observing wound-healing following amputation. Methods designed to create an external physical environment more conducive to wound healing have been developed. The immediate postsurgical rigid dressing has been used successfully in many cases, with the technique as originally developed and with individual modifications (1). For the last 3 years, PRS has treated selected below-knee amputations with a Controlled Environment Treatment technique using gas as a dressing medium with the residual limb enclosed in a clear polyvinyl chloride bag (2). The parameters controlled within the environment are the external pressure, temperature, gas composition, and biological content (air cleaned to 99.998 percent sterility).

It is theorized that by maintaining the air pressure surrounding the residual limb at a level higher than that of the surrounding atmospheric pressure, edema can be more effectively controlled. By cycling the treatment pressure between high and low stages, vascular refilling is allowed.

It is difficult to determine, by visual observation of the residual limb, the effectiveness of this technique in controlling edema. It is, therefore, desirable to develop a technique to measure continuously any changes in edema that appear within the residual limb during Controlled Environment Treatment (Fig. 1).
FIGURE 1. — Three elements of the instrumentation system. At top left, strain gages mounted on proving ring are seen sutured in place on residual limb. Transmission cables shown leading from transducer (strain gage) run to amplifier, shown below. Amplifier serves also as strain indicator with visual readout. Amplified signal is run to a strip chart recorder: top right photo shows typical strip chart produced.

BIOMECHANICAL MODEL

The biomechanical model developed to describe the amputated limb during the healing phase (the first 7 to 10 postoperative days) is that of a uniform cylinder with a hemispherical cap, the radius of the hemisphere being the same as that of the cylinder. Because the residual limb is horizontal, the hydrostatic head changes (pressure) are assumed to be uniform within the cylinder. If initially the incision runs horizontally across the hemispherical cap, and is assumed to be closed by n sutures spaced a distance s apart, a relationship in which the force acting on each suture is expressed as a function of the internal pressure can be developed. The tensile force f in the suture tends to compress the skin between the two inser-
tions of a given suture, but develops tension in the skin beyond. This portion of skin surrounding the incision is assumed to have a uniform but unknown stiffness $K_1$.

One side of the C-shaped proving ring of the transducer is tied into the suture, relieving tension in the suture near its insertion: the other side is anchored to a position conveniently removed from the incision. The transducer and its ties now bridge a small portion of skin on the hemispherical end of the limb. If the transducer/ suture material is assumed to have a stiffness $K_2$, the force $f$ is then borne by the parallel combinations of the two materials, skin and transducer. If the stiffness of the transducer ($K_2$) is much, much greater than that of the skin ($K_1$), as is probable, then the load may be assumed to be borne completely by the transducer. Therefore, the force normally acting on the suture alone across the incision is reflected in the tension sensed by the transducer.

**EXPERIMENTAL DESIGN**

The experimental instrument and method of application, developed to measure change in residual-limb edema, was based upon the following hypotheses:

1. The internal pressure of the essentially horizontal residual limb due to edema is uniform throughout the limb;
2. The measurement of changes in skin tension at any one point on the hemispherical cap accurately reflects changes in the internal fluid pressure (in the absence of hematoma);
3. The tangential strain (due to hoop tensile stress) of the skin is directly proportional to internal pressure;
4. The compliance of the strain-gage/suture material is infinitely rigid in comparison with the compliance of the underlying skin; and
5. Localized stress relaxation of the skin is not sufficient to compensate for changes of skin tension due to internal pressure.

The validity of these hypotheses is unproven at this point but each seems reasonable.

The instrumentation system developed consists of a strain gage, with its amplifier, recorder, and associated transmission cables mounted on the back of a Mk 1B CET machine (Fig. 2). The strain gage used was designed and developed specifically for this application: it consists of a split proving-ring with strain gages mounted to the ring to sense surface strain at the ring’s point of maximum bending moment. The tensile force is applied at the attached eyelets.
FIGURE 2. — The strip chart recorder is mounted on the rear of a CET machine. The amplifier is located on the top surface of the machine adjacent to the CET filter system.
FIGURE 3. — Diagram illustrating components of the strain gage.

(Fig. 3) by the suture material. All strain gages and terminal strips are coated with an acrylic air-drying coating and are encapsulated with RTV silicone rubber.

Each strain gage unit (transducer, amplifier, and cable) is calibrated by applying static loads through the eyelets and recording the output strain signal on a strain indicator. The output signals for five known loads are recorded twice for each value, and the linear response of the transducer is determined by using a linear regression curve fit. The output of each strain gage is therefore specified in terms of the load $Y$ in grams as the product of the regression coefficient and the output strain reading $X$ ($Y=AX$). The linearity of the fit is specified by the coefficient of determination $r$ and is provided for each strain gage unit.
The instrumentation employed for the measurement system is shown in Figures 1 and 2. The amplifier used is the model P350A strain indicator. This unit is selected because of stable square-wave strain gage excitation, variable gain, and recorder output capabilities.

The recorder used is the Omniscribe Model 5213-5, continuous low speed strip chart recorder. This unit features two-channel input at extremely low chart speed. The recorder was calibrated initially by measuring the pen deflection as static loads were applied to the transducer. The response of the recorder was quite linear over a wide range of loadings (except during the extremely low level load tested).

In pilot studies, the recorder was calibrated in the recovery room by adjusting the amplifier gain to correspond to 500 grams full load for full chart paper width. This was accomplished during the test by connecting a known resistor in parallel with the strain gage that had been previously measured in terms of output strain. This strain was then converted to load using the response curve of the given transducer unit, and the recorder was adjusted to deflect the appropriate number of divisions. During prototype tests a resistance that corresponded to a 200g load was superimposed on the signal and the recorder adjusted to deflect the pen 40 divisions.

The test protocol developed during the pilot study is as follows:

1. The strain gage unit to be installed should be connected to the strain indicator to determine zero-load strain reading, and then connected to the recorder to determine zero-load pen position, in pretest calibration of the equipment.

2. The strain gage (the transducer without cables) was delivered to the operating prep team for sterilization at least 36 hours in advance of its intended use. Gas sterilization only was used.

3. Installation of the strain gage at the time of surgery was performed according to the strain gage protocol (see “Suturing-in Strain Gauge”).

4. If Steri-Strips (3M Co.) are used, they should be applied before the final strain gage suture is tightened for preload. The strain gage should NOT be sutured over a Steri-Strip, as its stiffness is not known.

5. All cable connections are made in the recovery room. The initial preload readings, in terms of strain, are made from the strain indicator. The output of the strain indicator should then be connected to the strip chart recorder and initial preload measurement taken.

6. The tension measured by the strain gage should be recorded continuously on the strip chart recorder at 48 in.-per-day chart
speed, and intermittent strain readings with the strain indicator should be taken throughout the first 7 days of treatment. (The strain indicator readings require disconnection of the recorder cable at the strain indicator, to activate the strain indicator meter.)

**SUTURING-IN THE STRAIN GAGE**

We have found it convenient to locate the strain gage near the middle of the incision line. One end of the suture, after being tied off in the usual fashion, is looped through one eyelet of the strain gage (Fig. 4) and tied off. A loop length of approximately 2 cm is used to reduce the snubbing-post effect.

![Figure 4](image_url) - The transducer is attached to a skin suture. Point of instrument indicates other eyelet of ring. Cables from strain gage run down and to the right out of picture.
A second suture is placed distally 4 to 5 cm from the first suture (Fig. 5). This suture is looped through the remaining strain gage eyelet but not tied off.

At this point, Steri-Strips should be added if they are going to be used: care should be taken to ensure that no Steri-Strips pass under or over either tie-down sutures or the strain gage (Fig. 6).

After Steri-Strips are in place, the final suture can be tightened to place the strain gage under preload. (At this time, no specific amount of preload has been decided upon.) Figure 7 shows a sutured-in strain gage without Steri-Strips.

**ANALYSIS**

The continuous strip chart recordings of strain fluctuate with the CET operation and daily patient activity, as well as with long-term
edema changes. During pilot studies, the data were reduced to demonstrate mainly long-term edema control: the total strip chart record was reduced to a chart that fits data for the first 7 days of treatment on a graph measuring only 8 in. x 10 in. This compression of the data was accomplished by measuring the mean tension (halfway between maximum and minimum cyclic fluctuations) at each hour mark throughout the first 7 days. These loads were then plotted on a condensed scale to indicate long-term changes more readily.
PRELIMINARY RESULTS

The skin tension strain gage has been used successfully on three patients (Fig. 8). (Five subsequent patients have experienced minor equipment problems which invalidated their data.) This pilot study indicates that there is a distinctive increase in residual limb pressure, peaking a few days postoperatively and not in hours as one might expect.

On the fifth postoperative day, patient No. 1 was found to have compromised the pressure integrity of his treatment by inserting his hand in the seal. This allowed more air to escape, thus lowering the pressure, especially during the high pressure portion of the pulse cycles. The effect can be seen in the sharp rise in tension/edema: when the air pressure was restored, tension/edema reduced sharply (Fig. 8). No special techniques were used to monitor the patients, so it is not known if some of the other irregularities could be
attributed to the same cause.

This paper describes the preliminary work accomplished in developing an instrumentation system to indicate changes in the edema in the residual limb of below-knee amputees in the early postsurgical phase. The instrumentation described in this report has been demonstrated to function well, and appears to meet all original design criteria. Its reliability and representativeness can only be determined by its use in a long term comprehensive study.

REFERENCES
