Volume changes occurring in postoperative below-knee residual limbs

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Abstract—Comparative maturation rates of 36 below-knee postoperative, healed amputation residual limbs were observed. Measured were the limb volumes and circumferences. Three methods of residual limb stabilization were employed: 1) elastic wrap; 2) plaster cast and pylon; and, 3) plastic laminate socket and pylon. The limbs receiving the plastic laminate showed the most rapid stabilization, while the elastic wrap did not stabilize. Considerable variance existed in relations between variables. Correlation between limb circumference and volume was poor. However, in general, the rates of change, i.e., the relations between volume and time, and circumference and time, were statistically significant (p < .05).

INTRODUCTION

Since the early development of prosthetic devices for amputees, problems have existed in generating and maintaining a precise and accurate fit in the early posthealing and maturing periods. This problem results from the fact that exoskeletal prostheses require a precise and accurate relationship at the limb-to-socket interface. Forces generated during the gait cycle must be controlled by the prosthetic device in a manner that results in a comfortable and efficient gait.

The problem is most severe for the immature residual limb, one that is generally less than about 1-year postamputation. There are several characteristics that are unique to the immature residual limb. Specifically, the limb volume changes progressively during immaturity due to postoperative edema. Temporally, maximum volume occurs immediately postoperatively. In the healed limb, volume-shrinking methods such as elastic wrapping and/or ambulation help decrease residual limb edema. Our experience shows that the edema, in response to an efficient shrinking program, will largely subside during the first 2 months of the posthealing period, but muscle atrophy may continue for many months. The prime location of the edema is in the distal portion of the limb since this is where most of the healing and inflammatory reaction occurs. The effect of muscle atrophy on volume is directly related to residual limb length, because the long below-knee amputations include more of the anterior and posterior leg muscles. Thus, during the first 2 or 3 months of the posthealing period, when decreased edema alters limb volume, socket volume must be adjusted frequently. Only when the limb's volume changes have slowed to a relatively stable point should the fitting of a first permanent prosthesis be considered.

Several investigators have described methods to...
measure residual limb volume (2, 4, 5, 6). A National Academy of Sciences report (7) raised the issue of the need for objective information on the extent of changes with time, noting that limbs shrink for a considerable time following the surgery. Golbranson et al. (3) measured residual limb volume as a function of time to define the maturation process. They concluded that ambulation hastened maturation by increasing the shrinkage rate of the soft tissues. The mechanism by which this is accomplished was not found.

The purposes of this investigation were: 1) to evaluate three different residual limb volume reduction methods; 2) to establish methods for determination of the point of stabilization; and, 3) to determine whether circumferential measures can be considered reliable indicators of limb volume.

METHODS

Experimental

All subjects were recent unilateral, below-knee amputees with either a primarily healed residual limb or a secondarily healed granulating wound edge. No residual limb had previously been subjected to any shrinking method.

Three methods were employed to stabilize volume: a) elastic wrap (EW), b) plaster cast and pylon (PC), and c) plastic laminate and pylon (PL). Eligible subjects were placed serially into one of the three experimental groups. This method was used in order to fill all three experimental groups at about the same rate. While all patients were equally “qualified” for the elastic wrap group, all were not equally qualified for the plaster cast or the plastic laminate groups for a variety of reasons.

All experimental patients were taught limb wrapping techniques with an elastic wrap as soon as the rigid surgical dressing was removed. Patients were taught specific and general endurance exercises and encouraged to extend their knees to maintain joint mobility.

For the EW group, the standard figure-of-eight pattern was implemented, using one circular anchor wrap above the knee for each of the two four-inch-wide elastic bandages. The wrap was applied with moderate tension and was rewrapped every 4 waking hours—or as it loosened. In case of pain or discomfort, the patient was instructed to loosen the wrap.

For the PC group, the residual limb was covered with a Spandex sock (Knit-Rite, Inc., Kansas City, MO) and all bony prominences were padded with Sifoam (Scimedics, Anaheim, CA). The patient was fitted with a patellar tendon-bearing (PTB) plaster cast suspended by a waistband and fork strap. The proximal rim was determined by standard PTB trimlines. Distally, an adjustable device and a solid-ankle/cushioned-heel (SACH) foot was attached. The patient began ambulation between parallel bars, bearing weight to tolerance. After each ambulation session, the plaster cast was removed and the limb was wrapped in an elastic bandage as described above. When the patient demonstrated more tolerance, ambulation outside the physical therapy area was permitted.

For the PL group, the plastic laminate socket was made in accordance with established procedures for prosthesis fabrication. A negative mold was made of the residual limb, and the subsequent positive mold was modified according to standard practices. The laminate socket was made over a polyethylene foam liner. The suspension was a waistbelt with one strap attached to the PTB suspension cuff. Distally, an adjustable device and a SACH foot were attached. Ambulation was conducted as described above for the PC group.

Residual limb volume was measured by a water displacement method. The instrument (Figure 1) consisted of a transparent limb immersion tank with a calibrated overflow receiver and a metal framework to support and to raise and lower the tank assembly. The receiver, resembling a half pie on edge, was rotated about the overflow tube to register the volume of water displaced by the limb and also to return water to the tank when the limb was removed. A scale on the receiver, calibrated from zero to 1600 ml in 20-ml divisions, was used to measure displaced water volume.

A tension-spring cloth tape measure was used to measure limb circumference. (Cloth tape was used to allow conformation to soft tissues: the tension-spring feature reduced errors from tape tensioning variations.) Circumference measurements were recorded with a resolution of one-eighth of an inch.

Volume and circumference measurements were made weekly during the residual limb maturation phase (Phase I), and bimonthly after the fitting of the first permanent prosthesis (Phase II) until completion of the second phase. Completion of the
second phase was determined by one of three factors: a patient’s personal reason for discontinuing; clinical judgment about the residual limb-socket disparity or discomfort; or, termination of the research project.

In order to measure limb volume, the tank was filled to the level of the overflow tube. The operator then raised the water-filled tank to a height at which the subject could easily immerse the limb. This was done with the subject standing, supported on a walker, with the knee flexed to about 25 degrees. The limb was immersed to the lateral joint line, which was indicated by skin marking. (The joint line was palpated and re-marked at each measuring session, because skin tightening caused the marker to migrate off the joint line.)

Upon immersion of the limb, the displaced water overflowed into the receiver. The operator stabilized the limb in the tank to minimize disturbances and to maintain the level of immersion at the joint line. After water displacement, the subject removed the limb from the tank and the operator rotated the receiver until the water level in the receiver was aligned with the bottom of the overflow tube. Residual limb volume was then read from the calibrated scale at the level of the meniscus. The operator then rotated the receiver to zero volume and returned the water to the immersion tank. Volume measurements were repeated three times per session, recorded, and averaged.

Circumference measures were made at 2, 4, and 6 inches from the distal limb aspect using a right-angle device as a guide. Circumferences were measured, taking care to locate the tape at the marked locations and to tension the tape properly. At each session, the contralateral calf was measured at its point of maximal circumference to monitor general edema.

Patients were weighed without their prosthesis at each test session. This measurement was made with the subject balancing on one limb while standing between a pair of parallel bars.

**Statistical analysis**

In order to characterize the relationships between volume and time, and between circumference and
time, regression methods were used. Linear regression was used to determine the rates of change and to compare these rates among the three groups.

To compare general group characteristics (Table 1), one-way analysis of variance (ANOVA) was implemented. All analyses were performed using the BMDP statistical package (7) run on an LSI-11/23 + microcomputer (Digital Equipment Corp., MA). The level of statistical significance for all tests was set to p < .05.

Table 1.
BK volume/circumference data analysis summary.

1. Total number of subjects: 36
   - Elastic Wrap: n = 13
   - Plaster Cast: n = 10
   - Plastic Laminate: n = 13
2. Total number of test points: 640
   - Elastic Wrap: 263
   - Plaster Cast: 158
   - Plastic Laminate: 219
3. Average days followed: 338 (SEM)
   - Elastic Wrap: 271 ± 214 (59)*
   - Plaster Cast: 419 ± 406 (128)
   - Plastic Laminate: 328 ± 371 (103)
4. Average volume over study: 916 ml
   - Elastic Wrap: 997 ± 312 (87)
   - Plaster Cast: 908 ± 212 (67)
   - Plastic Laminate: 843 ± 368 (102)
5. Average 2-inch circumference: 11.7 inches
   - Elastic Wrap: 12.1 ± 0.80 (.22)
   - Plaster Cast: 11.8 ± 0.47 (.15)
   - Plastic Laminate: 11.3 ± 1.21 (.34)
6. Average 4-inch circumference: 12.4 inches
   - Elastic Wrap: 12.9 ± 0.97 (.27)
   - Plaster Cast: 12.2 ± 0.44 (.14)
   - Plastic Laminate: 12.1 ± 0.29 (.29)

*Significance difference between PC and EW group (p < .05)

RESULTS

Nearly 80 subjects were enrolled in the project, but more than half of them discontinued for a variety of reasons. The final database comprised 36 patients, distributed nearly equally among the three methods of residual limb volume reduction. The distribution was the following: 13 elastic wrap (EW); 10 plaster cast and pylon (PC); and, 13 plastic laminate and pylon (PL).

One of the objectives of the study was to identify a point in time at which to transfer test subjects from Phase I to Phase II; that is, to determine the time at which to fit the patient's first permanent prosthesis. During the course of gathering data, it became evident that volume stabilization was impossible to determine for more than half of the patients. Two graphs of limb volume versus time are shown in Figure 2. Subject JN exhibits a volume stabilization phenomenon—whereas subject TC does not. These examples illustrate that there was a great deal of variability among subjects in absolute volume and in volume-versus-time relationships. Time to fit the permanent prosthesis was therefore chosen arbitrarily in the following manner:

1) For the subject whose limb volume declined, stabilization was declared to have occurred when the rate of change diminished to 1.0 ml/day.
2) For the subject whose limb volume did not decline, the fitting was done after 70 days of observation.

One-way ANOVA revealed no significant differences among the three experimental groups for number of days followed in the study, absolute limb volume, absolute 2-inch circumference, and absolute 4-inch circumference, suggesting similarity of groups (Table 1).

In order to decrease between subject volume variability, volumes were normalized to the initial residual limb volume (defined as 100 percent). The remainder of the discussion refers to the normalized limb data.

Various curve-fitting techniques were tried in order to characterize the relations between volume and time, and between circumference and time. The linear means offered the best overall way to interpret rates of change. Lines representing the best linear fit to the average volume and circumference data for the three experimental groups are shown in Figure 3. For average volume (Figure 3a), both the PL and PC groups decreased significantly (p < .05), while the EW group showed no significant volume change over time. For average circumference (Figure 3b), the PL and PC groups demonstrated a significant decrease in circumference (p < .05), while the EW group actually demonstrated a significant increase in circumference (p < .05) with time. In all cases, correlation coefficients (indicating the "good-
ness of fit” to the line) were below 0.6, indicating poor linear fits (Table 2).

Correlation of limb circumference with limb volume was positive (Table 3). The best correlation was observed at the 2-inch level. In the case where volume and circumference increased (EW group), both were well correlated. However, the correlation was poor when volume and circumference declined.

The circumference of the contralateral calf was measured at each test session. Although changes occurred, they were never significant enough to warrant deleting residual limb circumference data due to lower limb tissue volume.

**DISCUSSION**

The relationship between residual limb volume and socket volume has been discussed by a number of investigators (3,4,5,6). The one most nearly resembling this project was reported by Golbranson et al. in 1968 (3). That study, dealing with immediate postsurgical prosthetic fittings, revealed spectacular improvement in the rehabilitation of young amputees, and in particular, of those without vascular disease. Noted in that 1968 study, in addition to shorter rehabilitation time and psychological benefits, was that the intensive ambulation portion of the program resulted in prompt and lasting decreases in residual limb volume. Having noted that, it is imperative to focus on factors that distinguish between the present project and studies of the past.

This project focused on geriatric amputees with vascular disease and other multiple system diseases. Geriatric amputees are frequently less than well-motivated to comply with an intense level of ambulation. It is significant that the geriatric patients with multiple system diseases such as cardiovascular abnormalities, musculoskeletal deficiencies, balance problems, and other pathology in the contralateral lower limb would not be able to achieve levels of ambulation expected in younger patients and those without significant disease. Moreover, this project was conducted within the definition of the *early fitting program* and not the 1968 *immediate postsurgical program*. To clarify this difference, the immediate postsurgical fitting program defines the parameter that the amputee ambulates the day after surgery in a temporary prosthetic...
device. In the early fitting program, the amputee does not ambulate in a prosthetic device until the residual limb is healed. In patients with a vascular compromise or diabetes, the healing process may be prolonged up to several months. In such situations, residual limbs have entirely different viscoelastic properties where the edema has subsided and there is a significant amount of fibrous tissue present. One should expect the influence of ambulation to be less, because that quality of tissue is more resistant to rapid change.

Despite those intervening factors, from the clinical point of view, this project indicates that the most efficient way of preparing and conditioning a limb for a permanent prosthesis is through the use of a well-fitting, molded socket. Such a procedure will tend to shorten the overall rehabilitation time of geriatric amputees as well as improving the quality of their lives during the rehabilitation period.

The results of this study demonstrate that the residual limb volume-reduction method affects the stabilization rate of the recent below-knee amputee limb. For the group of amputees examined in this study, treatment with the plastic laminate technique decreased the volume more quickly than treatment

Table 2.
Summary of linear regression of variables versus time.

<table>
<thead>
<tr>
<th></th>
<th>Volume</th>
<th>2&quot; Circ.</th>
<th>4&quot; Circ.</th>
<th>Avg. Circ.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entire group</td>
<td>m = -.011</td>
<td>-.0061</td>
<td>-.0015</td>
<td>-.0039</td>
</tr>
<tr>
<td></td>
<td>r = .13*</td>
<td>.20*</td>
<td>.073</td>
<td>.16*</td>
</tr>
<tr>
<td>Elast. Wrap</td>
<td>m = .015</td>
<td>.017</td>
<td>.0079</td>
<td>.013</td>
</tr>
<tr>
<td></td>
<td>r = .08</td>
<td>.32*</td>
<td>.19*</td>
<td>.28*</td>
</tr>
<tr>
<td>Plaster Cast</td>
<td>m = -.0062</td>
<td>-.0054</td>
<td>-.0038</td>
<td>-.0046</td>
</tr>
<tr>
<td></td>
<td>r = .16*</td>
<td>.30*</td>
<td>.26*</td>
<td>.30*</td>
</tr>
<tr>
<td>Plastic Lam.</td>
<td>m = -.022</td>
<td>-.015</td>
<td>-.0033</td>
<td>-.0091</td>
</tr>
<tr>
<td></td>
<td>r = .30*</td>
<td>.59*</td>
<td>.23*</td>
<td>.52*</td>
</tr>
</tbody>
</table>

\[m = \text{slope of regression curve in percent per day}\]
\[r = \text{coefficient of correlation}\]
\[* = \text{indicates significant effect of regression}\]
with the plaster cast technique. Moreover, treatment with the elastic wrap method actually increased volume with time.

Among the causes of the differential rates of volume decrease observed among the three groups, several factors appear to dominate. First, both the PL and PC groups were ambulatory, leading to the conclusion that weightbearing itself provides a stimulus for volume decrease. Second, the EW group presented with several factors affecting cardiovascular fitness. This finding was made based on an examination of the medical histories of 15 right BK amputees. Based on this study, it was found that the EW group may not be able to compensate for edema within the BK residual limb to the same extent as the PL and PC groups. However, this factor is probably secondary to the ambulation effect.

Three sources of error in volume measurements limited volume accuracy to about 30 ml. Sources of error included variation of water temperature and density, motion-induced wave action caused by the subject, and muscle contraction in the residual limb. These sources of error were considered small, relative to total volume.

Poor correlations between stump volume and either 2-inch or 4-inch circumferences (Table 3) suggest that circumference measurements cannot be simply substituted for volume measurements. In fact, the best correlation between volume and circumference was observed when volume increased (see EW group, Table 3). In the case where residual limb volume decreased, the correlations were poorer. This may imply that the mechanisms for limb swelling and shrinking are complex and differ in where and how changes occur. Possibly, swelling occurs primarily radially, while shrinking occurs both radially and axially.

While none of the experimental groups "stabilized" during the study period, several statements regarding residual limb stabilization can be made. First, volume does not simply decrease exponentially, as has been suggested by previous investigators (3). Periodic short-term and long-term variability (Figure 2) is such that a simple time course of volume over time cannot be determined. However, because the rate of decrease in residual limb volume was greatest in the PL group, it would be expected that this group would stabilize most rapidly. The actual time to stabilization for the EW group was clearly greater than 70 days (the extent of the present study). Qualitative interpretation of the data suggests that stabilization times range from 25 to 200 days for the entire 3-section (36 limbs) group. While these times were not determined using a quantitative criterion, they do provide a general estimate. Since stabilization appears to be a highly individualistic process, there seems to be merit in monitoring circumference during the postoperative period to serve as a guide in determining when to fit the first permanent prosthesis. A cautious view must be adopted, since the rate of change may be small (note slopes in Table 2).

Finally, as revealed by the results of this study, the plastic laminate socket approach offered the most rapid maturation. Although construction of a plastic laminate socket for use during the reduction period is initially more expensive, the results suggest some advantages. Early maturation of the residual limb can lead to improved comfort for the patient and to extending the life of the first permanent prosthesis. Both of these may be viewed as potential cost benefits.

CONCLUSIONS

1. The plastic laminate (PL) group provided the most rapid decrease in both volume and circumference. The plaster cast (PC) provided a modest rate, while the elastic wrap group (EW) showed an increase.

2. Circumference did not correlate well with volume. However, both circumference and volume changed in the same direction with time, demonstrating statistically significant relations with time.

3. Recent amputees with cardiovascular problems may not show reductions in residual limb dimensions with time.

4. Stabilization may not be possible to define, particularly if it is clinically inadvisable for the patient to ambulate during the first several weeks posthealing.

5. While stabilization is a highly individualistic process, there is merit in monitoring circumference during the postoperative period as a guide in determining when to fit the first permanent prosthesis.

6. A potential cost benefit may conceivably be realized with the use of the plastic laminate socket during the posthealing period before fitting the first permanent prosthesis.
ACKNOWLEDGMENTS

The authors would like to thank Donald Johnson for his assistance with data analysis and Norman Tang, Chief, Physical Therapy, and his staff for their assistance in performing some of the measurements.

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