Chapter 26
Physiological Principles of Physiotherapy

Waldemar L. Olszewski

Introduction

Lymphedema of the extremities is caused by insufficient transport of tissue fluid via the lymphatics. The inadequacy of the lymphatic conduits is most commonly caused: (a) by their obliteration after infectious inflammation and subsequent scarring, (b) by their interruption during lymphadenectomy, and (c) after local irradiation and trauma. Impairment of transport capacity is the consequence of anatomical lesions caused by destruction of valves, degeneration of muscle cells, and obstruction of lumen by clot and external fibrous scarring. In advanced lymphedema most collecting lymphatics are closed.[1] Tissue fluid water, proteins, migrating immune cells, and cellular debris accumulate in the interstitial space. Identifying the location of mobile tissue fluid accumulation in the extremity and the nature of the morphological changes that develop in skin and subcutaneous tissue, muscular fascia, and muscles are prerequisite to rational manual or pneumatic compression therapy.[2]

Sites of Accumulation of Lymph and Tissue Fluid in Lymphedema

Only approximately 5% of tissue fluid enters the sub epidermal lymphatics to become lymph, whereas 80% accumulates in the interstitial space of the subcutaneous tissue between the collagen bundles and around small veins. The remaining 15% is located above and below the muscular fascia and in the muscles.[2] Obstruction of the deep lymphatic system always causes fluid accumulation in the muscular compartment. This applies to the lower as well as the upper extremities.

W.L. Olszewski
Department of Surgical Research and Transplantology,
Medical Research Centre, Warsaw, Poland

B.-B. Lee et al. (eds.), *Lymphedema*,
DOI 10.1007/978-0-85729-567-5_26, © Springer-Verlag London Limited 2011

Morphological Changes in the Lymphedematous Skin and Subcutis

These are (a) hyperkeratosis, (b) thickening of the dermis with an increase in the collagen content and mononuclear infiltrates, (c) deposition of collagen in the subcutaneous tissue with formation of multiple fibrous septa, (d) growth of fat tissue, and (e) fibrosis and depletion of lymphocytes in lymph nodes deprived of lymph flow and afferent stimulatory signal from the drained regions. Generally, not only the water content, but also the dry mass of the soft tissues steadily increases. The processes of hyperkeratosis and fibrosis change the mechanical properties of the tissues; consequently, this brings about the requirement for application of high compression forces to propel fluid during massage.

Hydraulic Conditions in the Subcutaneous Tissue

The bulk of stagnant tissue fluid is contained in the subcutaneous tissue. Massaging of this tissue requires knowledge of local hydraulics. Until recently, human experimental data on lymph and tissue fluid physics have not been available in the pertinent literature. We undertook the task of measuring lymph and tissue fluid pressures in normal and lymphedematous human lower and upper limbs and, below, we present the recent data. These may differ from what has thus far been presumed. The lymph and tissue fluid pressure and flow values presented here may be useful for rational physiotherapy, including manual or pneumatic massage and elastic support. Lymph pressures were measured in cannulated leg lymphatic collectors, tissue fluid was recorded using subcutaneously implanted sensors and fluid flow was calculated from changes in limb circumference continuously measured with a strain gauge plethysmograph.

Pressures

Under normal conditions, lymph flows only during spontaneous rhythmic contractions of the lymph vessel wall at pressures from 0 to 10 mmHg, independently of body position. There is no hydrostatic component even in an upright position because, under normal conditions, collecting lymphatics contain only a few microliters of lymph in lymphangions separated by valves. There is no flow during the non-contraction (diastolic) period[3] In lymphedema, in the few non-obliterated lymphatic collecting vessels, the lymphatic pump is largely ineffective and there is a to-and-fro movement of lymph during limb muscle contractions.[4] Backflow is caused by valve insufficiency. Lymph pressures may reach levels above 100 mmHg in the upright position (the hydrostatic component not present in normal lymphatics) and during limb muscular activity.[4] Tissue fluid: mobile tissue fluid, even in very

Fig. 26.1 A recently designed deep tissue tonometer recommended for measuring tissue compliance. The length of the plunger is 10 mm and its cross surface area is 1 cm^2. Force is expressed in g/cm^2. The tonometer is pressed against the skin at a depth of 10 mm. Wings protect against pushing the plunger into the tissue deeper than 10 mm. The data obtained are helpful for setting proper pressure in the pneumatic compression devices (see Fig. 26.2)

advanced stages of lymphedema, reveals low pressures ranging from 0 to 10 mmHg.[4] Subcutaneous tissue acquires the anatomical structure of a sponge with thousands of fluid "lakes". Its anatomical structure creates hydraulic resistance to flow. To overcome this resistance, minimum fluid pressure of above 30 mmHg is required.[4,5]

Pressure Gradient Across Skin and Subcutaneous Tissue

It is expected that the external force applied to the lymphedematous tissues will partly dissipate in the fibrotic skin and subcutis as the rigidity of these tissues in lymphedema is significantly higher than that of normal tissues. Thus, the tissue fluid pressure during massage should be lower than that exerted by the massaging hand or the pneumatic sleeve. In order to measure the rigidity of soft tissues of the limbs, special tonometers have been designed by us. They measure the force required to create a standard 10-mm deep soft tissue indentation (Fig. 26.1). The readings of the force applied to tissues correlate with tissue fluid pressures created by the pressing tonometer (Fig. 26.2). For example, the tonometer was pressed into the swollen tissue at a depth of 10 mm and the force was 1,000 g/cm^2. The simultaneously measured tissue fluid pressure achieved 50 mmHg. In another subject with fibrous skin, a force of 1,500 g was needed to obtain fluid pressure of 50 mmHg. To move tissue fluid in the subcutaneous space the minimum pressure of 30 mmHg is required.[4] We plotted the applied force values against the generated tissue fluid pressures at various levels of the lower limb. A curve was drawn that allowed us, knowing the tonometer values, to predict the pneumatic sleeve

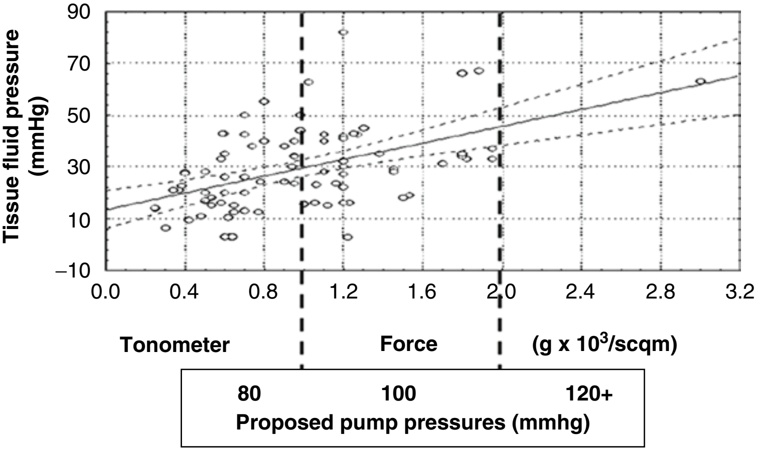

Fig. 26.2 Correlation between tonometer applied force and tissue fluid pressure in lymphedematous calves (stages I–IV). Measurements were carried out at six levels of the limb (above the ankle, at mid-calf, below and above the knee, at mid-thigh, and below the inguinal fossa). For the application of the tonometer see the text. In each case the tonometer was pressed 10 mm deep. With increasing skin and subcutaneous rigidity (depending on the stage of lymphedema), more force had to be applied to obtain fluid pressures between 30 and 70 mmHg. The minimum fluid pressure to move tissue fluid is 30 mmHg. A tonometer force of 1,000 g/cm^2 would give the recommendation for 50–80 mmHg in the pneumatic sleeve. Tonometer values of 1,500 g/cm^2 and 2,000 g/cm^2 would be a hint to set sleeve pressures of 100 and 120 mmHg respectively (80 tests, $X=13.534+16.140^{*}\,Y$, corr. coeff. = 0.48389 CI95%)

pressures necessary for obtaining fluid pressures above 30 mmHg and initiating flow (Fig. 26.2). A tonometer value of 1.0 kg/cm^2 would give the recommendation for 50–80 mmHg in the pneumatic sleeve. Tonometer values of 1.5 and 2.0 kg/cm^2 would be a hint to set sleeve pressures of 100 and 120 mmHg respectively (Fig. 26.2).

Conditions for Creating Centripetal Tissue Fluid Flow

The tissue fluid flow should be directed proximally and there should not be any backflow. To obtain efficient flow, high external pressures should be applied, overcoming the natural hydraulic resistance of the tissues. They depend on mechanical compliance of the skin. We believe that applying compression pressure close to 100 mmHg, or above, is not harmful to the tissues because the compression force is acting in a perpendicular and not horizontal direction. Also, as tissue fluid flow is extremely slow, there is no shear stress. To avoid backflow after manual massage, immediate distal bandaging of the limb (minimum pressure 40 mmHg) should be carried out, and, during sequential pneumatic massage, the distal sleeve chambers should not be deflated.

Manual Massage

Indications

Manual lymphatic drainage has been reported to be effective when used in combination with other anti-edema modalities, such as complex decongestive therapies, as well as in combination with intermittent compression pumping.[6-8] Manual massage has been very effective in subjects with segmental disfigurement of the limb (e.g., excessive swelling at the ankle level), at sites where the pneumatic sleeve cannot be adjusted to the shape of the extremity.

Advantages and Shortcomings

Advantages: (a) "softening" of fibrotic tissues especially in patients with very hard skin, (b) local mobilization of stagnant tissue fluid at sites of highest accumulation, and (c) moving fluid from disfigured parts of the limb not suitable for pneumatic massage. There are also some shortcomings. External pressures exerted upon a small massaged area (masseur's hand area) not embracing the entire limb do not build up fluid pressures high enough to initiate centripetal flow. Short time intervals of hand compression are not sufficient for effective centripetal tissue fluid flow to be generated and, upon hand release, the fluid backflow occurs. Manual compression does not stimulate intrinsic lymph and tissue fluid flow.[9] Massaging should be followed by immediate bandaging of the distal segments of the limb.

Manual Massage Hydraulics

In tissue fluid pressures generated by hand massage, the therapist does not know how much pressure he generates at various tissue depths. Based on the results of our studies, these pressures range from 40 to 120 mmHg and are disseminated radially at a distance of only 3 cm (Fig. 26.3).[4,5] Removal of the massaging hand brings about an immediate drop in tissue fluid pressure and, as a consequence, a cessation of flow (Fig. 26.4).

Pneumatic Massage

Indications

Every case of lymphedema of the lower or upper extremity is suitable for pneumatic massage.[10] The contraindications are: active dermatitis, skin ulcer, and recent venous thrombosis.

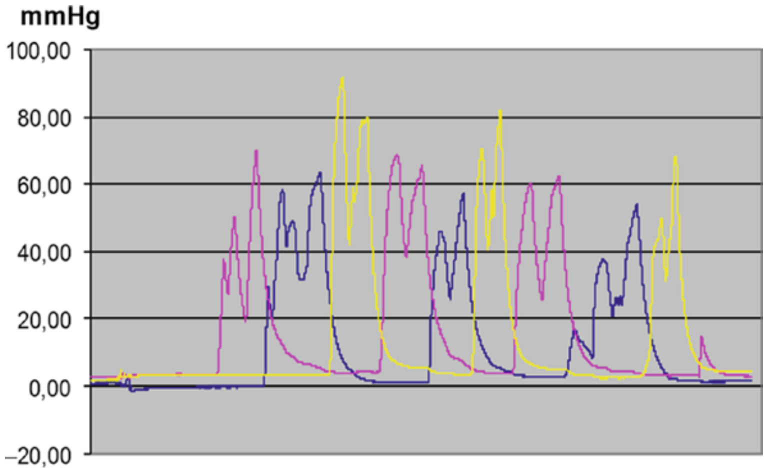

Fig. 26.3 Tissue fluid pressures in the subcutaneous tissue of a lymphedematous calf during manual massage. The therapist's hand was placed at three levels: above the ankle, in the mid-calf, and below the knee. There were three consecutive hand compressions at each level. The hand force generated pressures of 40–90 mmHg, although the therapist tried to use the same force. Cessation of hand compression caused a rapid drop in pressure, allowing fluid backflow

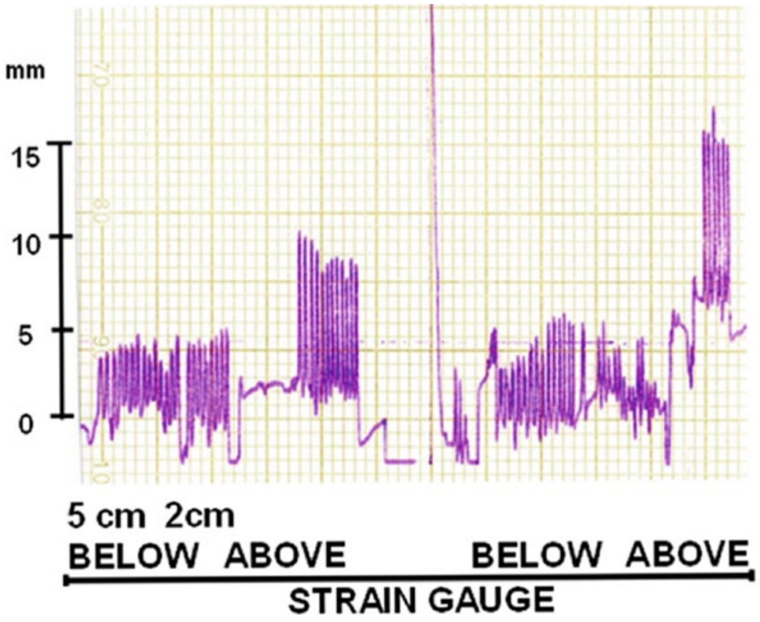

Fig. 26.4 The strain gauge was placed in the mid-calf during manual massage for continuous measuring of the increase in circumference. Each hand compression produced a short-lasting increase in the circumference proximal to the compression site, to decrease suddenly after the release of hand pressure. This was followed by fluid backflow to the tissue pit. It proves that there is a lack of fluid proximal flow. Scale 15 mm = 5 mm circumference increase = 10–15 ml tissue flow

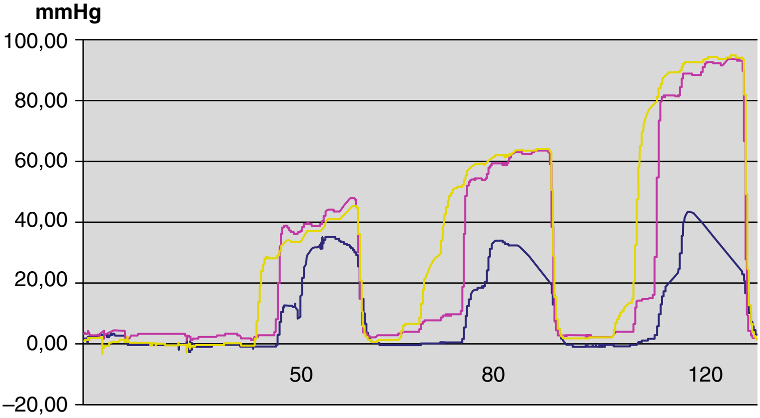

Fig. 26.5 Tissue fluid pressures measured subcutaneously during sequential pneumatic compression at pressures 50, 80, and 120 mmHg of a lymphedematous calf. Pressure sensors were placed at a depth of 5–7 mm above the ankle, in the mid-calf and below the knee. During first inflation, the pressure curve above the ankle increased to 25 mmHg although the sleeve chamber pressure was 50 mmHg. The second curve in the mid-calf rose to 40 mmHg only. The third curve was low as fluid easily flowed to the popliteal fossa with loose tissue. Similarly, tissue fluid pressures were lower than in sleeves at the inflation pressure of 80 and 120 mmHg. A high gradient between the inflated sleeve chamber and tissue fluid was due to hard fibrotic skin

Advantages and Shortcomings

The advantages are: (a) tissue fluid is moved proximally in the whole compressed fragment of the limb embraced by the sleeve; (b) sequential compression creates unidirectional fluid stream reaching the groin or arm region during one cycle, (c) it keeps distal chambers non-deflated, during sequential inflation of the proximal ones, which protects against fluid backflow; (d) the procedure is easily performed by the patient, can be repeated several times per day, and does not engage additional care labor; (e) it can be applied in large cohorts of patients. The shortcomings are: (a) it has little effect in very advanced stages of lymphedema with hard skin, and (b) its high cost.

Pneumatic Compression Hydraulics

The sleeve pressures that we recommend, based upon the tissue fluid pressure that we have measured during pneumatic massage, range between 50 and 120 mmHg.[4,5] The level of applied sleeve pressure depends on the rigidity of the soft tissues. We believe that, the higher the rigidity, the higher the applied pressures should be. Soft tissue tonometry helps to set an effective sleeve pressure. Note that tissue fluid pressures are, in each case, lower than those in the sleeve (Fig. 26.5).[4,5] The time needed

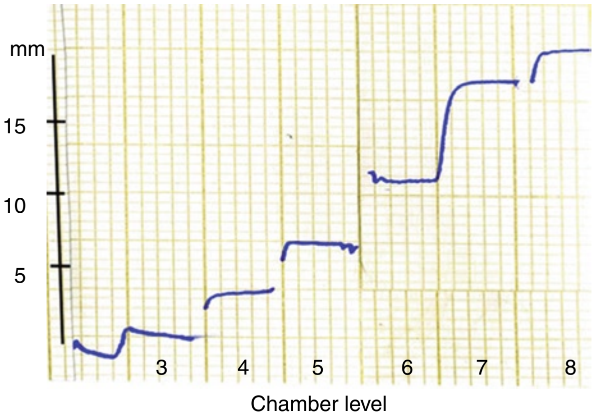

Fig. 26.6 A strain gauge was put around the limb at six levels and changes in the circumference generated by proximal fluid flow during sequential pneumatic compression were recorded. Inflation of consecutive sleeve chambers moved fluid in the proximal direction from 3 to 8. Changes in circumference were recalculated into volume. Inflation time 55 s, sleeve pressure 120 mmHg. This method allows the tissue fluid flow to be quantitated and the effectiveness of the compression device to be evaluated[4]

for inflation of the sleeve chambers should be long enough to reach an effective tissue fluid pressure (above 30 mmHg) and initiate flow. Data originating from debulking surgery, when the surgeon uses the fingers to squeeze fluid from the incised tissue to facilitate the excision procedure, indicate that 50–90 s is a minimum time period necessary to mobilize tissue fluid. Contemporary pumps are set at only 5–20 s. The distal chambers of the sleeve should be kept inflated to prevent fluid backflow and blood inflow with subsequent stasis in the superficial venous system of the limb. Deflation should occur simultaneously in all chambers. Continuous measuring of circumference changes during the sequential compression cycle provides insight into the moved fluid volume (Fig. 26.6).[4,5]

Remarks for Users of Compression Devices

We predict that high tissue fluid pressures are necessary to propel fluid proximally because of the rigidity of the skin and subcutaneous tissue, the low hydraulic conductivity of tissues (collagen excess, fibrosis), and the flow hindrance at the groin and axilla level. The fluid pressure head is always lower than that in the sleeve. Pressure is low in areas with loose connective tissue (popliteal, groin, arm pit), and padding of these regions is helpful for prevention of fluid accumulation. Tissue fluid channels are formed during long-term pneumatic massage taking over the fluid transportation burden from the obliterated lymphatics.[11] Groin tissue and the inguinal crease as well as the arm pit are the main anatomical barriers for the massaged tissue fluid to flow to the non-edematous tissues of the hypogastrium and hip or shoulder.

References

1. Rijke AM, Croft BY, Johnson RA, de Jongste AB, Camps JA. Lymphoscintigraphy and lymphedema of the lower extremities. *J Nucl Med*. 1990;31:990-998.
2. Olszewski WL, Jain P, Ambujam G, Zaleska M, Cakala M. Where do lymph and tissue fluid accumulate in lymphedema of lower limbs caused by obliteration of lymphatic collectors. *Lymphology*. 2009;42:105-111.
3. Olszewski WL. Contractility patterns of human leg lymphatic in various stages of obstructive lymphedema. *Ann NY Acad Sci*. 2008;1131:110-118.
4. Olszewski WL, Jain P, Ambujam G, Zaleska M, Cakala M, Gradalski T. Tissue fluid pressure and flow in the subcutaneous tissue in lymphedema – hints for manual and pneumatic compression therapy. *Phlebolymphology*. 2010;17:144-148.
5. Olszewski WL, Jain P, Ambujam G, Zaleska M, Cakala M, Gradalski T. Tissue fluid pressure and flow during pneumatic compression in lymphedema of lower limbs. *Lymph Res Biol.* 2010; (in press).
6. Szolnoky G, Lakatos B, Keskeny T, Varga E, Varga M, Dobozy A, Kemeny L. Intermittent pneumatic compression acts synergistically with manual lymphatic drainage in complex decongestive physiotherapy for breast cancer treatment-related lymphedema. *Lymphology*. 2009;42:188-194.
7. Andersen L, Højris I, Erlandsen M, Andersen J. Treatment of breast-cancer-related lymphedema with or without manual lymphatic drainage – a randomized study. *Act Oncol*. 2000;39:399-405.
8. Vignes S. Management of following breast cancer lymphedema. *Bull Cancer*. 2007;94: 669-674.
9. Olszewski WL, Engeset A. Intrinsic contractility of prenodal lymph vessels and lymph flow in human leg. *Am J Physiol*. 1980;239:H775-H783.
10. Brennan MJ, Miller LT. Overview of treatment options and review of the current role and use of compression garments, intermittent pumps, and exercise in the management of lymphedema. *Cancer*. 1998;83(12 suppl):2821-2827.
11. Olszewski WL, Jain P, Ambujam G, Zaleska M. Newly formed tissue fluid channels take over the fluid flow burden in long-lasting lymphedema of lower limbs. *Lymph Res Biol*. 2010; (in press).