Identification of viscoelastic parameters of skin with a scar in vivo, influence of soft tissue technique on changes of skin parameters

Hana Vránová a,*, Josef Zeman a, Zdeněk Čech b, Stanislav Otáhal a

a Department of Anatomy and Biomechanics, Faculty of Sport and Physical education Charles University, Prague, Czech Republic
b 2nd Medical School Charles University, Prague, Czech Republic

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Summary The goal of the experiment was to develop an identification method capable of objective detection of changes of viscoelastic properties of skin with a scar remaining after a modified radical mastectomy. We compared the intact skin and the skin with a scar, a scar before and after physiotherapy. We used two methods. The first one is based on measurements of the local dynamic deformation response of the skin and the second one is the matrix identification of static deformation that identifies properties of the whole tested region of the explored tissues. We identified the skin stretchability, shiftability against deeper layers and deeply analysed both the methods. In some patients, we found statistically proven difference. In all these cases the measurement methods have detected changes of the observed tissue condition. We found both methods to be potentially applicable after further improvements as a diagnostic tool, which can contribute to the improvement of postoperative care of patients.

Background This study is focused on patients with a large scar after a surgery on a sensitive place of their body namely, patients after modified radical mastectomy (MRM). We shall specifically consider patients with a large scar because they share myofascial pain or restricted range of motion and some other postoperative problems as a result of the scar. All human systems are functionally and structurally interconnected. Changes of skin behaviour also causes functional changes in other systems, for example the respiratory system (Petruš, 2003), lymphatic (Wald et al., 1999) and neuromuscular systems (Lewit, 2003). A large scar on the chest area can cause changes of sensitivity not only on the chest itself, but also on the...
whole operated side of the manipulative system of the arm. Patients after MRM can also have psychological problems (Pasini, 2002).

A large scar changes mechanical behaviour of the skin, because of disturbances in the natural tissue morphology its nature, texture, and skin lines described by Langer, Borges, Kraisl (Williams et al., 1989; Cerda, 2005).

The skin is often considered in different experiments as a phenomenon (Clark et al., 1996; Nielsen et al., 2002; Dougal et al., 2003) or as a simple membrane (Cerda, 2005), although the skin is a multilayer tissue (Carola et al., 1992; Zuijlen et al., 2002). The skin thickness varies on different parts of the body, from less than 0.5 mm to more than 5 mm (Clark et al., 1996). From a biomechanical point of view, the skin is a complex composite biomaterial (Agache and Humber, 2004), where each layer mutually interacts. In our experiment, we shall consider the skin as a membrane for simplicity. It is still difficult to study individual components in our conditions, however we can theoretically consider that ‘layering’ of the skin is important for a mutual shift of the skin with respect to subcutis or smoothness and optimum range of motion. Mechanical skin properties are the basis for the considered objective detection of changes in skin properties (Agache and Humber, 2004).

From a purely mechanical viewpoint, the skin is considered as a visco-elastic system, the main properties of which are viscosity and elasticity (Kvasnica et al., 2004). The main component for description of visco-elastic behaviour of the skin from the biomechanical point of view are protein fibres of connective tissue in dermis and hypodermis (collagen and elastin), which determine its toughness and stiffness and also amorph matrix which determines viscosity (Agache and Humber, 2004).

The skin is regenerated by a relatively high-quality tissue (contrary to cartilage). The important role for biomechanical properties of the skin in the healing process involves many factors, and one of them is the activity and capability of fibroblasts, cells of the connective tissue. Fibroblasts produce protein fibres and also amorph matrix (Williams et al., 1989). The collagen bundle in dermis appears randomly organized. The healing result of the damaged skin depends also on external factors, such as the surgical wound or after burns, etc. (Carola et al., 1992).

From the histological point of view, skin with a scar has a different architecture of collagen fibres in the dermis (Zuijlen et al., 2002) compared with healthy skin. The architecture of collagen bundles of scar tissue is arranged in a more parallel fashion with the skin surface. Histological examinations by one or two observers using polarized light is the most common method to determine the collagen orientation (Zuijlen et al., 2002).

Our in vivo experiments are a part of a broader project, dealing with a biomechanical description of intact skin, and skin with a scar, and the possibility of physiotherapy (after MRM). For the treatment of patients we used the methods of soft tissue techniques; according to Lewit (Lewit, 2003).

These experiments should also serve for a clinical practice in order to optimize timing of physiotherapy procedures and as a feedback for the treatment. These identification methods could also contribute to changing the attitude towards the post-surgical patients, where a large scar remains in a sensitive area that can sometimes restrict the activity of daily living.

**Importance of physiotherapy**

Physiotherapy has some methods and approaches available to detect some states of discomfort in the neuromuscular system when an overload is not yet perceived, for example as a pain (Véle, 1995; Lewit, 2003). Palpation is one of the important diagnostic tools, but it is nonsemantical information (Véle, 1995) and requires some experience. In physiotherapy, we evaluate the relevance of the active scar by an examination called the “barrier phenomenon”. We treated the active scar with soft tissue techniques, mostly by using a “release phenomenon” (a form of localised myofascial release) (Lewit, 2003). The therapeutic effect was sometimes immediate (improvement of range of motion, reduced sensitivity around the scar, etc.).

By associations with the motor system the viscoelasticity of the skin has influence to distant body places, where the change of skin behaviour can manifest as an overload and pain in muscles within trigger points. Clinical experience suggests that changes in the behaviour of skin can influence whole global motor patterns, or stability of the neuromuscular system (Lewit and Olšanska, 2003). Respiratory capacity is also often reduced in the area of the operated body side (Petruš, 2003).

Our hypothesis is that subjectively observable changes of a scar caused by applied physiotherapy (improved skin behaviour) are also observable by objective means involving measurements of physical properties of viscoelasticity of the scar tissues in vivo.

**Methods**

**Local dynamic deformation response (LDDR)**

**Model and its calculation**

The first identification method (Dougal and Klemera, 2002) is based on a classical reological description of subjected tissue. Reology and bioreology describe properties of their subjects through simplified reological models (Kvasnica et al., 2004). We use this simplification to identify changes of skin parameters. It is usually difficult to solve relationships in biomaterials, therefore models are introduced, which approximately describe a character of deformation behaviour of various groups of materials. Linear models are used to model and calculate determined parameters. These models contain linear elements (see Figure 1) and corresponding motion equations are then linear differential equations with constant coefficients (see equations below). This method uses very small deformations, so that linear model can be used.

The reological model of skin visco-elasticity schematically depicted in Figure 1 was used for our experiment and was designed by Dougal and Klemera (2002). This model consists of two serially connected subareas. The subarea implementing so called ‘fast’ component, is in the upper part of the picture. This subarea is composed of three elementary elements connected in parallel: an elastic element $H_1$, a viscose element $M_1$ and an inertial element
M(mass). The so called ‘slow’ component is depicted in a lower part of Figure 1. This part consists only of two in parallel connected elements: an elastic element \( H_2 \) and a viscose element \( N_2 \).

The global system motion (time course of a return of the deformed skin to a normal position) can be decomposed to two components which correspond to the two areas of the model, the fast component and the slow component.

Time courses of individual components can be described as follows:

- **The fast component**
  
  \[
  f(t) = L \left[ 1 - e^{-kt} \left( k \sin(\omega t) - \omega \cos(\omega t) \right) / \omega \right]
  \]

  where \( \omega = 2\pi f \).

- **The slow component**
  
  \[
  g(t) = P(1 - e^{-\alpha t})
  \]

- **The total deviation** \( h \) is a sum of fast and slow components due to its serial arrangement. Thus, its time course of the global system is
  
  \[
  h(t) = g(t) + f(t)
  \]

The following model parameters are then calculated for individual measurements:

- For the fast component:
  - the steady deformation value \( (L) \) depends on elasticity,
  - the damping time constant \( (k) \) of a dynamic response depends indirectly on viscose and directly on elastic coefficient,
  - the frequency \( (f) \) of damped oscillations depends on stiffness.
- Analogically, the following parameters were identified for the slow component:
  - the steady deformation value \( (P) \),
  - the damping time constant \( (q) \).
- The derived parameters of the ensemble were further identified, which were composed from parameters of individual components:
  - the total deformation response in a steady state \( (P/L) \),
  - ratio of parameters \( (P/L) \).

Elasticity and inertia are dominant in a fast component at the expense of viscosity. On the other hand, viscosity dominates over elasticity in a slow component.

The method used in our experiment is based on identification of individual material constants of the considered model. This method is based on measurement of dynamics of return of the observed tissue from the distorted to normal state according to Důbal and Klemera (2002). Very small local deformation of an observed tissue occurs during the measurement due to a measurement stylus, which is impressed into a measured tissue. After vanishing of the transition action connected with a skin deformation, the deforming force acting towards the stylus jumps to a minimum level assuring only a contact of the stylus with the measured tissue. After a decrease of the deformation force, the transition effect of the tissue returns towards the original state.

The measuring stylus is pushed back by a tissue and its motion is recorded. A diagram of the experiment is schematically shown in Figure 2.

By means of the Fourier and Laplace transforms, the material constants of the assumed model are then obtained from the time course of a return of the deformed tissue to its original state. Obtained model parameters (material constants) then directly correspond to concrete physical quantities and properties of the observed tissue.

This method identifies properties of skin only in the small neighbourhood of a testing stylus. Selected mechanical model also does not involve and distinguish properties of individual skin layers.

The experiment was performed in vivo on tested persons. For each person a basic set of measurements consisted of partial measurements of the skin with a scar.
and a reference measurement of a healthy tissue (e.g. on the same side of a chest aside from the scar). Every partial measurement was repeated several times. For each person the whole set of measurements was performed first before and again after a targeted physiotherapeutical treatment of the skin with a scar. Material constants of the assumed reological model of measured tissue were identified for each individual partial measurement. Obtained sets of material constants for affected tissue before and after the therapy were mutually compared with the goal to confirm or reject the experiment assumptions, i.e. that, by means of calculated material constants it is possible to reliably and objectively detect the subjectively observable changes in properties of a skin with a scar caused by the performed therapy.

Obtained result sets were mutually compared by a Wilcoxon (rank-sum) test, the aim of which is to refute that two compared quantities (individual partial quantities of a scar before treatment and after treatment) are from the same observation space, i.e. they have the same properties. This test was chosen first because it gives exactly the required information (identifies a difference between compared samples, i.e. whether the change took place) and also because it can work well with small and different-sized samples without regard to normality of sample data (in contrast to t-test). Our result sets had 8–14 observations for individual quantities.

Results of LDDR method

Results obtained from the Wilcoxon test are arranged into the following table. The table presents combined results of two patients. We have successfully treated and measured four relevant patients and we analysed measurement data of two of them. Individual material constants are in table-rows, compared pairs of measurements are in columns. Table 1 has the following interpretation:

- Combinations represented by a symbol 0 are the ones for which a statistical difference of the given quantity between two given states was not demonstrated.
- Combinations represented by a symbol + are at the boarder of demonstrability.
- Combinations with a statistically important difference are bold printed. One or two asterisks indicate that both medians differ with a reliability of 0.95 or 0.99, respectively.

### Table 1: Composed results of Wilcoxon test of patients.

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<thead>
<tr>
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<th>Intact–scar</th>
<th>Intact treatment</th>
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<td>P/L</td>
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Matrix identification of static deformation (MISD)

### Material and method

As a contrast to the first mentioned measurement method (LDDR) we started a development of a measurement method capable of observing larger area of affected skin and capable of distinguishing shiftability of tissue layers.

A deformation of a skin is identified through the observation of deformation of a matrix of test marks that are printed on the skin in a relaxed position. It consists of 144 marks and has a dimension 60×60 mm.

The measuring device is schematically depicted in Figure 3. The base of the device has two stands (1), which hold pulleys (2) and a horizontal connecting pole (8). The pole stabilizes the stands and also holds a camera (9). On a table (6) lies a tested person on whose skin is printed a matrix of test marks (7). Along two opposite sides of a matrix are fixed drawing stakes (5), which are longer than the side of a matrix and deliver relatively homogenous distribution of a deformation force. Drawing stakes are attached to drawing strings (3) with attached weights (4). The weights generate a constant deformation force 20 N each. In this experiment were 2 kg chosen weights mainly not to cause any pain.

One measurement consists of capturing the matrix state (positions of individual test marks) before application of the deformation force and after application of the deformation force, after finishing of all the transition effects. Matrix states are captured by a camera and mutual displacements of individual test marks are then analysed graphically and numerically. Changes of mutual distance of test marks are proportional to the local deformation rate. Every examination consists of two measurements, one before and one after a targeted therapeutic treatment.

With this method, it is possible to measure the elasticity of skin as well as its shiftability against the subcutis. When a symmetric deformation force is applied to both sides of an observed region, then it is possible to observe mostly its own elasticity. With a deformation force applied only to
one side of an observed region, shiftability of skin can be watched, respectively, the distribution of deformation in the observed region (e.g. in front of and behind the scar). Both these parameters can be measured in various directions (e.g. along and across the scar) to observe highly anisotropic properties of the skin.

Only a simple analysis of obtained data was performed. Respective snapshots were aligned and fields of vectors showing mutual displacements of individual test marks were constructed. Aside of a graphical analysis also a basic numerical analysis was performed consisting of calculating and comparing average vector lengths. We demonstrate here one of the patient after MRM—6 years after surgery.

We demonstrate 4 vector fields describing the following cases:

1. Deformation by a symmetric load
   a. before a therapy,
   b. after a therapy.
2. Deformation by an asymmetric load
   a. before a therapy,
   b. after a therapy.

Figure 4 shows a vector field created by a symmetric load before any therapy and Figure 5 shows the same tissue under the same conditions only after a targeted therapy. The change of the vector field due to softening of the hardened tissue is evident.

Figure 6 shows a vector field of the same tissue before any therapy, but created by an asymmetric load and Figure 7 shows the same tissue under the same conditions only after a targeted therapy. In this case the change of a vector field is caused mainly by releasing of barriers (adhesions) of skin layers in a scar which cause nonhomogeneous distribution of deformation.

Results

So far we have successfully tested 3 patients (after MRM) with the second mentioned method (MISD). From the demonstrated vector fields at one of them, the following evidence can be derived:

- **Symmetric load:**
  - Average length of vectors before treatment is 22.8 pix and after treatment is 28 pix. The tissue is due to a treatment more elastic and allows more stretching. This supports the assumption that the treatment causes a global releasing and softening of a tissue, which is otherwise hardened due to a scar.
  - Approximation of a vector field before a treatment is also evidently more bent and passes closer to the center of the area than in the case of after the therapy. This also confirms the supposed effect of the therapy on a global softening and increasing elasticity of the tissue which is otherwise hardened.

- **Asymmetric load:**
  - Average length of vectors before treatment is 37.1 pix and after treatment is 48.6 pix. This again confirms apparent increase of elasticity but also
signals releasing of adhesions between skin layers which protects their mutual shifting.

- Approximation of a vector field before a treatment is also evidently more bent than is the case of after the therapy. Skin with an untreated scar is nonhomogeneous and the main source of nonhomogeneity is the scar which protects a deformation to spread behind it, resulting in a bend of a deformation vector field.

The therapy improves the properties of a scar so that its behaviour is more close to an intact skin which is demonstrated by a more homogeneous, less distorted vector field of deformation. This also confirms the supposed effect of the therapy on a global softening and increasing elasticity of the tissue which is otherwise hardened and also on releasing adhesions developed in a scar. The patients subjectively indicate improvement of sensitivity on the area with a scar.

**Conclusion**

All patients from our study were examined and treated according to Lewit (2003), we mainly used the barrier phenomenon. The experimental group (7 patients after MRM) were tested by LDDDR method (4 patients) and MISD method (3 patients). These two experimental methods; although they need further development, especially the MISD method, did prove the global assumption that the changes of tissue properties due to the performed therapy, up to now detectable only by subjective means, can be also reliably and objectively detected by these methods. After further development these methods may help towards a better understanding of the compensation mechanisms of large scars, and to improve control and focusing of an early consequent therapy of large scars in general.

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**References**


