Correlation Between the Static and Dynamic Stiffness Indices of Medical Elastic Compression Stockings

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BACKGROUND  Compression therapy with medical elastic compression stockings (MECS) has been used effectively for treating patients with chronic venous insufficiency for many years.

OBJECTIVE To study the correlation between static stiffness and the dynamic stiffness index of 18 different brands of MECS.

METHODS In all, 18 different brands of MECS were divided into 5 categories (class II round-knit, class II flat-knit, class III round-knit, class III flat-knit, and class IV flat-knit) and tested. The tension of the textile of the MECS at the B1 level was measured according to the Institut de Textile France method to calculate the static stiffness index. The dynamic pressure pulsations were measured with a newly developed dynamic pressure-determining device to calculate the dynamic stiffness index.

RESULTS The results showed that there was a positive correlation between the static stiffness index and the dynamic stiffness index. The dynamic stiffness indices were higher than the static stiffness indices.

CONCLUSION Although the stiffness of MECS is a further refinement to the current classification, which classifies MECS according to the pressure they exert at the B level, the dynamic stiffness index does not have any additional value over the static stiffness index as far as the classification of MECS is concerned. Either or both of these characteristics should be used to select the most suitable MECS for the patient.

The Artificial Leg Segment Model was on loan from R. Stolk, Research and Development Department of Varitex, NV. MECS were provided without charge by the various manufacturers.

Medical elastic compression stockings (MECS) are effective in the treatment of chronic venous insufficiency and are particularly effective under dynamic conditions. They work, among other things, by improving venous hemodynamics and reducing edema.1,2 This can be ascribed to their characteristics, the most important being elasticity and stiffness. MECS exert pressure on the leg because of their elasticity, and they can prevent and treat edema because of their stiffness. According to the European Committee for Standardization (CEN) stiffness is defined as the increase in pressure at the B level if the circumference increases by 1 cm and is expressed in millimeters of mercury per centimeter or hectopascals per centimeter.3 There are several devices and methods, such as the Hatra and the Hohenstein methods, for determining the static stiffness of MECS.4 These methods are based on the same principle; the MECS is clamped into the device, and the force that is required to stretch the MECS can be used to calculate the static stiffness. However, these laboratory techniques are far from actual use. Therefore, other methods have been developed to determine the dynamic stiffness of MECS in order to explain their behavior and how they work in actual use, such as during walking.

In the evaluation of compression therapy in general and MECS in particular, it is important to reach consensus. Most of the literature on MECS is unfortunately neither evidence-based nor comparable. There is a need for easy and internationally comparable evaluation methods and consensus on the classification of MECS. In a recently published consensus statement, several recommendations were reported.5 It was proposed that measurements at the...
B1 level should always be included in all measurements with compression devices in the future, with the exact location of the sensor situated at the segment that shows the largest increase in circumference during dynamic conditions, such as maximum dorsiflexion, standing up from the supine position, and walking.

There has been an increasing interest in the characteristics of MECS, and new aspects of this topic, such as the dynamic stiffness index, have been studied. However, one must remain critical and question the additional value of a dynamic stiffness index over the static stiffness index.

The aim of this study was to determine whether there was any correlation between the static and the dynamic stiffness indices in 18 different brands of MECS from well-known manufacturers, with the intention of establishing a parameter, namely dynamic stiffness, that would enable the exact behavior of MECS to be predicted under dynamic conditions. It is essential in daily practice to know whether there is any correlation between the static and dynamic stiffness indices, because although static stiffness is much easier to determine, it does not reflect the dynamic condition, and static stiffness alone cannot explain the difference between the therapeutic effectiveness of MECS belonging to the same compression class.

Materials and Methods

Medical Elastic Compression Stockings

We arbitrarily chose 18 different brands of MECS from well-known manufacturers. All MECS were custom-made for B1 leg-size of 22 cm and were divided into the following 5 categories based on the compression class and type of the knit: class II round-knit MECS, class II flat-knit MECS, class III round-knit MECS, class III flat-knit MECS, and class IV flat-knit MECS. There was no specific reason for choosing different numbers in the three compression classes. There is usually more choice in class II and class III MECS. None of the manufacturers were aware that the MECS were being tested.

Test Procedure

Before testing, all MECS were washed according to the European guidelines, followed by hydroextraction (maximum of 2 minutes) and flat drying. The MECS were conditioned at least 12 hours before the measurements.

Measuring Point

Measurements were performed at the B1 level, the point at which the Achilles tendon changes into the calf muscles. We chose the B1 level because the largest differences in circumference during dynamic changes occur at this level. Moreover, measurements at this level are according to the recently published recommendations of Partsch and colleagues. A marking-board with an adjustable clamp to fix the MECS was used to mark the measuring positions.

Static Stiffness

To determine static stiffness, we used the Institut de Textile France method. This method uses a dynamometer with which the tension in a section of the MECS held between two movable T-pins can be measured (Figure 1). After the MECS was marked, it was stretched between two bars. To avoid constriction of the knit, the upper bar consisted of three separate parts. Only the middle part was attached to a tension tester load cell. The knit was stretched to its maximum circumference 6 times. The maximum force in the sixth cycle that was required to stretch the MECS to its full extent conforming to its B1 size is converted into pressure using the Laplace formula: $T = P \times R$, where $T$ is tension or traction, $P$ is pressure, and $R$ is radius. The pressure was expressed in mmHg.

Static stiffness was calculated after 3 different measurements per MECS were taken. First, pressure was measured for a girth that was 1 cm smaller than the B1 size. Second, pressure was measured for
the B1 size (the so-called “real girth”). Third, the pressure for the girth that was 1 cm larger than the B1 size was measured. The MECS were made for a B1 size of 22 cm and were tested for the girths of 21, 22, and 23 cm. Static stiffness was then calculated using the following formula as described in our previous study.\\(^6\)

\[
\text{Stiffness} = \frac{\text{Pressure at B1 size, girth 23} - \text{Pressure at B1 size, girth 21}}{2}
\]

**The Dynamic Stiffness Index**

To determine the dynamic stiffness index, a dynamic leg-segment model was used to simulate walking and to investigate the dynamic behavior of MECS. This model has been described in detail elsewhere, but the method is discussed briefly.\\(^7\) The measuring

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**Figure 1.** Institut de Textile France method. The B1 section of the medical elastic compression stockings is clamped between the two bars. Note the middle part of the upper bar, which is attached to the tension tester load cell.
device consists of four components and is shown in Figure 2:

(1) A form wheel for simulating walking patterns. In a previous study, we analyzed changes in the circumference of the leg during walking with regard to the gait cycle, amplitude, and form of the signal. For this purpose, volunteers walked on a treadmill with mercury-filled rubber gauges around the leg at the B1 level. Changes in circumference were measured with strain-gauge plethysmography.

(2) An air-pressure generator (Posthumus Products, Haarlem, The Netherlands) connected to the form wheel that delivers a dynamic pressure signal to the air-filled drum. The air-pressure generator can be adjusted for the frequency and the amplitude of the signal and provides the air-filled drum of the artificial leg segment with precise pressure in such a way that the dynamic variation in circumference of the MECS equals 1 cm.

(3) An artificial leg-segment consisting of an air-filled drum covered with a rubber skin. An air-filled drum with the same circumference as the leg circumference at the B1 level was used for our measurements. Then the MECS was put over the leg segment. Changes in the circumference were registered with strain-gauge plethysmography. The pressure in the air-filled drum was recorded with a TruWave pressure-transducer (Baxter Healthcare Corporation, Irvine, CA).

(4) The pressure and the changes in circumference were measured simultaneously and fed into a computer system, the Fysio Flex system, built at the instrumentation service unit of the University of Nijmegen, The Netherlands. A registration curve of a dynamic measurement is shown in Figure 3.

The dynamic stiffness index was defined as the increase in pressure when the variation of circumference equalled 1 cm at a frequency of 1 Hertz (1 Hertz = 1 gait cycle per second). The dynamic stiffness index was then calculated.

Each brand of MECS was measured 3 times.

**Statistics**

Static stiffness and dynamic stiffness with corresponding standard deviations in the 18 brands of
MECS were calculated. The mean dynamic stiffness index with standard deviation was calculated from these 3 replicate measurements. SPSS 12.0.1 software was used for statistical calculations. To study the correlation between the static and dynamic stiffness indices, Pearson correlation coefficients ($r$) were determined.

**Results**

**Static Stiffness**

The results of the static stiffness tests at the B1 level of 18 different brands of MECS are shown in Table 1. It can be seen that the static stiffness index ranged from 1.70 mmHg/cm (Venotrain Soft) to 6.11 mmHg (Mediven Forte), with 1 outlier of 10.32 mmHg (class II Mediven 550). There was variation in static stiffness not only between the 5 different categories of MECS, but also within the 5 different categories. Static stiffness was independent of compression class and type of knit.

The dynamic stiffness values at the B1 level were much higher and are also shown in Table 1. The mean dynamic stiffness index ranged from 16.06 mmHg/cm at 1 Hz (Venotrain Soft) to 32.21 mmHg/cm at 1 Hz (class II Mediven 550). If the Mediven 550 stocking is removed from the calculation because of its outlier status in static stiffness, then the maximum mean dynamic stiffness index is 29.95 mmHg/cm at 1 Hz (class III Mediven 550). Variation in the dynamic stiffness index was noted not only between the 5 different categories of MECS, but also within the 5 different categories. Thus, the dynamic stiffness index is also independent of compression class and type of knit.

**TABLE 1. The Static and the Dynamic Stiffness Indices of 18 Brands of Medical Elastic Compression Stockings (MECS)**

<table>
<thead>
<tr>
<th>Brand of MECS</th>
<th>Static Stiffness (mmHg/cm)</th>
<th>Dynamic Stiffness Index* (mmHg/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class II 23 to 32 mmHg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Round knit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luxovar Prestige</td>
<td>2.63</td>
<td>18.45 ± 0.40</td>
</tr>
<tr>
<td>Mediven Elegance</td>
<td>2.87</td>
<td>16.15 ± 0.92</td>
</tr>
<tr>
<td>Mediven Plus</td>
<td>3.52</td>
<td>17.89 ± 0.15</td>
</tr>
<tr>
<td>Venotrain Soft</td>
<td>1.70</td>
<td>16.06 ± 0.27</td>
</tr>
<tr>
<td>Flat knit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neo Duna</td>
<td>2.88</td>
<td>18.62 ± 1.04</td>
</tr>
<tr>
<td>Flebossense</td>
<td>3.95</td>
<td>26.26 ± 1.06</td>
</tr>
<tr>
<td>Flebovar</td>
<td>2.95</td>
<td>23.34 ± 1.09</td>
</tr>
<tr>
<td>Mediven 550</td>
<td>10.32</td>
<td>32.21 ± 1.19</td>
</tr>
<tr>
<td>Eurostar</td>
<td>2.91</td>
<td>23.62 ± 0.89</td>
</tr>
<tr>
<td>Juzo 3022</td>
<td>3.78</td>
<td>19.45 ± 0.40</td>
</tr>
<tr>
<td>Juzo 3052</td>
<td>3.39</td>
<td>22.79 ± 0.79</td>
</tr>
<tr>
<td>Class III 34 to 46 mmHg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Round knit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luxovar Prestige</td>
<td>3.18</td>
<td>19.06 ± 0.53</td>
</tr>
<tr>
<td>Mediven Forte</td>
<td>6.11</td>
<td>23.06 ± 0.35</td>
</tr>
<tr>
<td>Flat knit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neo Durelna</td>
<td>2.60</td>
<td>21.23 ± 0.26</td>
</tr>
<tr>
<td>Mediven 550</td>
<td>6.72</td>
<td>29.95 ± 0.92</td>
</tr>
<tr>
<td>Euroform</td>
<td>4.88</td>
<td>24.22 ± 1.63</td>
</tr>
<tr>
<td>Class IV &gt; 49 mHg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flat knit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Euroform special</td>
<td>4.42</td>
<td>26.00 ± 0.59</td>
</tr>
<tr>
<td>Neo Durelna special</td>
<td></td>
<td>22.23 ± 0.59</td>
</tr>
</tbody>
</table>

*Calculated from three replicate measurements per brand.

**Figure 3.** Registration curve of a dynamic measurement. The red signal represents the circumference variation. The amplitude of this signal equals 1 cm. The blue signal represents the pressure variation in the air-filled drum.
Table 2 shows the variation in the range of the static and dynamic stiffness indices in the 5 different categories. With the exception of the class II round-knit MECS, the mean static stiffness and dynamic stiffness of the categories lie close together. Although there is a large variation in static stiffness as well as in the dynamic stiffness index in all 5 categories of MECS, it can be seen that the standard deviations (SDs) of static stiffness in the two categories of class II round-knit MECS and class IV flat-knit MECS are lower than those in the other categories. The SDs of the dynamic stiffness index in the three categories of class II round-knit, class III round-knit, and class IV flat-knit MECS are lower than those in the other categories. The overall tendency was toward a larger variation in static and dynamic stiffness in the flat-knit categories. The number of MECS in the various categories was small.

**Correlation**

A strong and positive Pearson correlation coefficient \( r = 0.79 \) with a clinical significance at the .01 level between static and dynamic stiffness index was observed, as shown in Figure 4.

**Discussion**

Compression therapy with MECS is highly effective under dynamic conditions, although most of our knowledge about the effectiveness of MECS is based on static (laboratory) testing. Because measuring dynamic pressure and stiffness on the human leg are difficult, there is an increasing need for accurate and reproducible laboratory methods for investigating the behavior of MECS under dynamic conditions. In the current study, we compared static stiffness measured using a slightly modified, approved technique with dynamic stiffness measured using a new device.

A large variation in the static and dynamic stiffness indices was observed not only between the 5 different categories of MECS, but also within the categories. Such large variations in static stiffness between and within compression classes corroborate those reported in our previous study.\(^6\) This means that the static and dynamic stiffness indices of MECS are independent of their compression class or

<table>
<thead>
<tr>
<th>Type of MECS</th>
<th>Static Stiffness Index (mmHg/cm)</th>
<th>Dynamic Stiffness Index (mmHg/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
</tr>
<tr>
<td>Class II round knit (n=4)</td>
<td>1.70</td>
<td>3.52</td>
</tr>
<tr>
<td>Class II flat knit (n=7)</td>
<td>2.88</td>
<td>10.32</td>
</tr>
<tr>
<td>Class III round knit (n=2)</td>
<td>3.18</td>
<td>6.11</td>
</tr>
<tr>
<td>Class III flat knit (n=3)</td>
<td>2.60</td>
<td>6.72</td>
</tr>
<tr>
<td>Class IV flat knit (n=2)</td>
<td>4.42</td>
<td>5.55</td>
</tr>
</tbody>
</table>

SD = standard deviation.
the type of knit and therefore may be of additional value to the current classification of the compression classes. Therefore, it would be highly desirable for the manufacturers to mention the stiffness and the pressure of the MECS on the packaging.

A positive correlation between the static and dynamic stiffness indices at the B1 level was observed. This means that, when a stocking has high static stiffness, it will also have high dynamic stiffness. The same is true when the static stiffness is low. For that matter, a stocking is no different from a compression bandage. The higher the stiffness or the stiffer the material, the bigger the pressure differences and thus the bigger the pressure amplitude. This is what we refer to as the massaging effect of MECS. Partsch and colleagues reported that inelastic bandages were more effective in reducing deep venous refluxes than elastic bandages.8 On the one hand, the higher the stiffness of MECS, the more they behave as inelastic material and the more effective they are in preventing edema, decreasing venous refluxes and improving the calf muscle pump function.8,9 On the other hand, they are less patient friendly because they are more difficult to put on and take off. We also know that, as the pressure of the MECS increases, they will be less comfortable for the patient. It is well known that patients in wheelchairs with dependency edema are difficult to treat. One is able to create more options for optimal treatment for the patient by varying pressure and stiffness.

If one seeks an explanation for the underlying working mechanism of MECS, then one must focus on the dynamic method, because this method closely approaches actual use. The observed differences between static stiffness do not contribute to this, because these differences are within the tolerance limits of manufacturing. Several methods are available to measure static stiffness. We chose the Institut de Textile France method because it is a validated and highly reproducible method, as we reported earlier.6 Above all, the CEN accepts this method as the reference method. Various studies have been published on different methods of measuring stiffness dynamically.2,10,11 All these methods have their advantages and disadvantages. Although the method that was used in this study is time-consuming and not applicable in daily practice, the problem with interface-pressure measurements is that the test locations, which are determined by the specific anatomic structure and body shape of the individual human leg, easily influence the pressure.12 Therefore, we consider our method to be the most exact method to determine the dynamic stiffness index.

To our knowledge, this is the first study in which static and dynamic stiffness indices were both calculated to see whether there was any correlation between them. No correlation studies on static and dynamic stiffness indices are available. We have used the method approved by the CEN to determine static stiffness, although it was measured at the B1 level, and according to the CEN, static stiffness should be determined at the B level. Although there is no difference in pressure between the B and B1 level, there is a difference in circumference. This would mean that the method used for measurements in this study is not comparable with other methods in which measurements are conducted at the B level.

It is not surprising that there was a positive correlation between static and dynamic stiffness. Stiffness is a characteristic of the material, in this case the knit, and this material does not alter under static or dynamic conditions. However, we should not ignore the role of hysteresis. Stiffness and hysteresis are important characteristics of MECS and are closely related. Putting it more strongly, they can neither be regarded nor measured independently of each other, and although there is a correlation between static and dynamic stiffness, the influence of hysteresis is probably greater under dynamic than static conditions.

The way stiffness is measured is a point of discussion. In a recent study, we calculated the static stiffness of different class II MECS.6 The difference between the minimum and the maximum static stiffness of class II MECS was approximately 5.5 mmHg. In the current study, the difference between the minimum and maximum static stiffness
for all MECS was approximately 8.5 mmHg. However, if we exclude the class II Mediven 550, because it is an outlier and is more than 10 mmHg/cm, then the difference is approximately 5 mmHg. These differences are within the tolerance limits of manufacturing. The effectiveness of the MECS cannot be explained based on these differences. It does not matter for classification whether static or dynamic measurements are conducted as long as one strives for a comparative method. It is unnecessary to calculate the dynamic stiffness index for daily practice. The prescriber has adequate information to assess how the MECS is likely to behave on the basis of 3 categories of static stiffness, namely, low, medium, and high.

Finally, based on the results reported here, we would recommend that the manufacturers mention the stiffness (static, dynamic, or both) and the pressure of MECS on the packaging. The dynamic stiffness may be of additional value for the current classification. We believe that the combination of stiffness (static and/or dynamic) and pressure would enable the prescribing physician to evaluate the effectiveness of MECS for a given venous insufficiency more accurately in daily clinical practice.

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References

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COMMENTARY

It is good of the authors to remind us that the clinical efficacy of a compression device depends not only on the pressure exerted on the leg, but also on the stiffness of the product. According to the European Committee for Standardization (CEN), stiffness is defined as the increase in pressure exerted by a compression stocking at the ankle level related to a theoretical increase of the leg circumference of 1 cm.
Following the instructions of the CEN document, the authors performed laboratory measurements with different medical compression stockings showing good correlation between the originally recommended static measuring procedure and a newly developed test mimicking the dynamic situation of walking. As a practical suggestion to the manufacturers of compression hosiery, it is proposed that stiffness values should be declared on the package in addition to pressure ranges.

Translated into clinical terms, stiffness characterizes the pressure changes under a compression device during walking. With each step, there is an increase in the leg circumference during muscle systole that will raise the compression pressure depending on the elastic property of the textile. Stiff, nonstretchable or short-stretch material will lead to high pressure peaks (high working pressure), whereas yielding, elastic material will produce only small pressure waves. Several experiments have clearly shown that the higher “massaging effect” of stiff material corresponding to the higher pressure amplitudes during exercise leads to a more-pronounced improvement of the venous pumping function in patients with chronic venous insufficiency. The massaging effect of medical compression stockings is lower than that of multilayer bandages.

The reported stiffness values obtained using in vitro testing are certainly able to discriminate between different products, but the transversal stretch of the stocking by 1 cm performed in the laboratory can hardly be compared with what is happening on the leg during walking, where the stretch with every step will be much smaller. Measuring leg circumference and subbandage pressure simultaneously on human legs, an Italian group 1 found much smaller changes in leg circumference at B1. Concentrating on several kinds of bandages, these authors have shown that the stiffness of a final bandage can be assessed only by measuring the pressure changes in different body positions in vivo and not according to laboratory specifications of the single textiles.

We have compared the stiffness of different compression stockings using in vivo and in vitro measurements of the same product. 2 The difference between standing and supine pressure at B1 was taken as a parameter for “static stiffness” in vivo, and slices from the same stockings cut from the B1 area were tested using an extensometer in the laboratory. There was good correlation between the stiffness measured on the leg and in the laboratory. Putting two class I stockings over each other increased not only pressure, but also stiffness, both in vivo and in vitro. Depending on the individual configuration of the limb, differences between the laboratory data and the actual effect on the leg are inevitable. Therefore the pressure ranges declared by the manufacturers can only be given for a range of leg circumferences. When in future trials physiological effects of compression stockings on individual patients are investigated, it will be desirable to assess pressure and stiffness of the material on the tested leg and not just to rely on a range of data declared by the producer.

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