Bioelectrical Impedance Measuring Method for Standing Load Evaluation

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Abstract: A bioelectrical impedance method was used to evaluate the workload in standing jobs. This method is designed to indirectly evaluate swelling of the lower leg by measuring the change in the rate of impedance of the lower leg. In this paper, we studied the relationship between the methods used for swelling evaluation, and studied the measuring conditions of the impedance method by using bioelectrical models. Furthermore, impedance in ten male subjects in three types of standing conditions was measured to check the validity of the model analysis. The results are as follows: 1) The result of theoretical analysis showed that the change in impedance caused by leg swelling is equal to the value obtained by the leg volume measuring method, and twice as great as the value obtained by the leg circumference measuring method. The rate of change in impedance at low frequency is about 4 times greater than that at high frequency. The low frequency impedance measuring method is therefore much more sensitive than the other methods. 2) The results of experimental studies showed that the impedance in the lower legs was reduced as the function of time when quietly standing for 30 mins. The change in the rate of impedance was 6.86±4.54% (mean±SD). This rate is 3-5 times greater than the data reported by other researchers who used volume measurement or impedance measurement at high frequency. This difference fits the results of model analysis, and proved the validity of model analysis and the usefulness of the impedance method as an index of the standing load. The effect of exercise on impedance and the relationship between impedance and subjective discomfort in the lower leg is also discussed.

Key words: Workload, Working postures, Standing, Leg swelling, Impedance

Many workers work in a standing posture in manufacturing and service industries. Evaluation of the workload involved in long hours of standing is quite important in preventing lower leg problems such as swelling, varicose veins and thrombosis. To evaluate leg swelling, leg circumference, leg volume and bioelectrical impedance in the lower legs are measured.

1) Leg circumference: This method is the simplest and easiest to use because we can do it with a tape measure only, but the change in leg circumference is small, and difficult to measure precisely. Onishi et al. used a strain gauge to keep the tension of the tape measure constant.

2) Leg volume: The method is a direct one used in measuring the level of swelling of the lower leg. Winkel developed an apparatus for this method. The apparatus includes a tank filled with water. The subject puts his leg into the tank, and the volume of lower leg is measured by the water level in the tank. A disadvantage with this method is that subjects have to take off clothing before measuring, making it very hard to perform repeat measurements. Pottier et al. and Winkel et al. used a modified method for foot volume measurement. Their method is effective in reducing the trouble involved in measuring, because subjects put only their feet rather than their whole legs into the tank.

3) Bioelectrical impedance: The method is an indirect one, and widely used for analysis of fluid dynamics or body composition. Stick et al. applied this method to evaluate the muscle pump of the lower legs in standing conditions. Shvartz et al. used it to evaluate leg swelling in prolonged sitting.

The impedance method is preferred to the other methods for continuous measurement without dis-
The relationship to other methods and the measuring conditions needed to evaluate the standing load have not been sufficiently studied. The aim of our research is to clarify this point by using bioelectrical models, and check validity in experimental studies.

Theoretical analyses of impedance

1. Relationship between impedance and leg swelling

A bioelectrical model of the lower leg is shown in Fig. 1. The shape of the lower leg is assumed to be a cylinder (radius of the base: \( r \)). It is also assumed that the swelling occurs equally at any position in the leg and \( r \) changes according to the level of swelling. The impedance (\( Z \)) and the rate of change in \( Z \) in relation to \( r \) (denoted by \( \Delta Z\% \)) are expressed by the following formulae:

\[
Z = \frac{1}{\sqrt{r^2}}
\]

\[
\Delta Z\% = -2\Delta r\% \quad \cdots (1)
\]

where

\( \rho \): constant of the resistance rate

\( l \): length of the lower leg

\( \Delta r\% \): rate of change in \( r \) (= \( \Delta r/r \times 100 \))

Using this model, the leg circumference (\( L \)), leg volume (\( V \)) and rate of change in \( L \) and \( V \) in relation to \( r \) (denoted by \( \Delta L\% \) and \( \Delta V\% \), respectively, \( \Delta L\% = \Delta L/L \times 100 \), \( \Delta V\% = \Delta V/V \times 100 \)) are also expressed by the following formulae:

\[
L = 2\pi r
\]

\[
\Delta L\% = \Delta r\% \quad \cdots (2)
\]

\[
V = \frac{4}{3}\pi r^3
\]

\[
\Delta V\% = 2\Delta r\% \quad \cdots (3)
\]

According to formulae (1), (2) and (3), the absolute value for the change in the rate of \( Z \) is as same as that for \( V \), and twice as great as that of \( L \). It is therefore clear that the method of measuring \( L \) is less sensitive than the other methods.

2. Tissue impedance and swelling level model

The equivalent circuit for a tissue bioelectrical model is shown in Fig. 2.\(^9,10\). It consists of resistance of extracellular fluid (\( R_e \)), resistance of intracellular fluid (\( R_i \)) and capacitance of cell membrane (\( C_{em} \)). The impedance of the tissue (\( Z \)) is given by the following formula:

\[
1/Z = 1/Re + 1/Ri \times \{1 - 1/(1 + 2\pi f C_{em} R_{i} j)\}
\]

where

\( f \): frequency of measuring current

\( j \): imaginary unit \( (j^2 = -1) \)

Acute reactions to prolonged standing cause an increase in extracellular fluid.\(^11\) This can be detected as the reduction in \( Re \). The rate of change of \( Z \) to \( Re \) at low and high measuring frequencies is as follows:

\[
Z_L = Re
\]

\[
\Delta Z_L\% = \Delta Re\% \quad \cdots (4)
\]

\[
Z_H = Re/R_i + Re \quad \cdots (5)
\]

\[
\Delta Z_H\% = R_i/(R_i + Re) \cdot \Delta Re\% \quad \cdots (5)
\]

where

\( Z_L \): \( Z \) in low frequency \( (f \leq 0) \)

\( Z_L\% \): rate of change in \( Z_L \) (= \( \Delta Z_L/Z_L \times 100 \))

\( Z_H \): \( Z \) at high frequency \( (f \geq \infty) \)

\( Z_H\% \): rate of change of \( Z_H \) (= \( \Delta Z_H/Z_H \times 100 \))

\( \Delta Z_H\% \): rate of change in \( Re \) (= \( \Delta Re/Re \times 100 \))

Comparing the formulae (4) and (5), we see \( \Delta Z_L\% \) is 1 + \( Re/R_i \) times larger than \( \Delta Z_H\% \). Considering that \( Re/R_i \) is 3.2±1.2 (mean±SD), as reported by Watanabe et al.\(^12\), \( \Delta Z_L\% \) is about 4 times larger than \( \Delta Z_H\% \). Therefore, to evaluate acute reaction to leg swelling, \( Z \) at low frequency is proved to be more useful than \( Z \) at high frequency which was generally used for the analysis of fluid dynamics or body composition.

The evaluation of chronic (monthly or yearly) reaction to standing loads is more complex, because the cause of leg swelling is not limited to the dynamics of extracellular fluid. The hypertrophy of extracellular tissues also occurs when the leg swelling is prolonged. This reaction causes a reduction in both \( Re \) and \( Ri \). It is therefore necessary to measure \( Z \) at high frequency, but prolonged standing jobs may also cause hypertrophy or atrophy of the muscles of the lower leg as a result of the physiological adaptation. It also causes an increase or decrease in leg circumference or volume. In these conditions, it would be hard to evaluate the stand-
ing load by measuring circumference, leg volume and impedance in the lower leg.

**Experimental study**

1. Subjects and methods

The subjects of the study were ten healthy men who were not suffering from edematous diseases, varicose veins or injury to the lower leg. The median age, body weight, stature and obesity index determined by the Broca-Katsura method were 24 yrs (range 23–26 yrs), 64 kg (range 59–75 kg), 168.5 cm (range 163–180 cm) and 0.79% (range −5.6–32.3%), respectively. Impedance (Z) in the right leg was measured under the following three standing conditions:

1) Quiet standing: The subjects kept standing straight on both feet for 30 min. All leg movements were inhibited.

2) Iterative exercise and standing: The subjects did iterative exercise (walking on the spot for 1 min) and quiet standing (for 9 min) three times.

3) Continuous walking: The subjects walked for 120 min at a constant pace of 1 m/s.

Each standing condition was carried out on a different day to avoid the interaction of the standing loads. Eating and drinking were inhibited while standing.

We developed an impedance meter which was controlled by a computer so as to measure Z automatically at constant intervals. The block diagram of the apparatus is shown in Fig. 3. Z was measured by the four-electrode method. The measuring conditions were as follows: frequency: 5KHz, current: 333 μAms, electrode: disposable disc type Ag/AgCl electrode (Nihon Koden, Vitrode M-150, Japan), distance between detecting electrodes: 15 cm, distance between detecting and current electrodes: more than 5 cm, intervals between measurements: 2 min.

Leg circumference (L) and the subjective discomfort score (DS) were also measured to compare with Z. The leg circumference was measured at the largest portion of the right lower leg with a tape measure. No device to maintain tape measure tension was used. It was measured only before and after standing. The subjective discomfort score was obtained with reference to foot pain, dullness in the lower leg and knee pain. Each score point was recorded at one of 10 levels (1: lowest, 10: highest), and average scores for the three points were used as DS. The subjective discomfort score was obtained every 2 mins.

To determine the change in the Z and DS patterns during standing, the normalized Z and DS were computed by using the mean and standard deviation (SD) for each subject. Furthermore, the values for ΔZ%, ΔL% and ΔDS were also computed by means of the following formula to evaluate the total effect of standing:

\[
\Delta Z\% = \frac{Z_A - Z_B}{Z_B} \times 100 \\
\Delta L\% = \frac{L_A - L_B}{L_B} \times 100 \\
\Delta DS = DS_A - DS_B
\]

Fig. 4. Normalized Z and DS in quiet standing.

Fig. 5. Normalized Z and DS in iterative exercise and standing.

Fig. 6. Normalized Z and DS in continuous walking.
Table 1. Changing rate of Z, L and DS

<table>
<thead>
<tr>
<th></th>
<th>Quiet standing</th>
<th>Iterative exercise and standing</th>
<th>Continuous walking</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean±SD(%)</td>
<td>mean±SD(%)</td>
<td>mean±SD(%)</td>
</tr>
<tr>
<td>ΔZ%</td>
<td>-6.86±4.54</td>
<td>-5.89±6.22</td>
<td>8.95±11.87</td>
</tr>
<tr>
<td>ΔL%</td>
<td>0.81±1.24</td>
<td>0.51±1.21</td>
<td>-0.20±1.14</td>
</tr>
<tr>
<td>ΔDS</td>
<td>2.73±1.65</td>
<td>1.50±0.85&lt;0.001(*)</td>
<td>3.90±2.43</td>
</tr>
</tbody>
</table>

The p-values are calculated by paired t-test from the data before and after standing. * indicate 5% of significant difference.

where

\[ Z_B, L_B, DS_B \] measured values for Z, L and DS before standing

\[ Z_A, L_A, DS_A \] measured values for Z, L and DS after standing

2. Results

The temporal changes in normalized Z and DS are shown in Figs. 4 to 6. A decrease in Z and increase in DS were clearly observed as shown in Fig. 4. A similar pattern of change was also obtained in the data for iterative exercise and standing, as shown in Fig. 5. An increase in Z and decrease in DS were observed just after the exercise, but the effect was small and short ranged. In the data for continuous walking, a simple pattern of increase in Z and DS was observed.

Table 1 summarizes the values for ΔZ%, ΔL% and ΔDS and the results of the statistical test. The absolute values for ΔZ% were larger than those for ΔL% under all conditions. Five percent significant differences were observed in Z and DS under all conditions in a two-tailed paired t-test. The absolute values for ΔZ%, ΔL% and ΔDS for quiet standing are larger than those for iterative exercise and standing, but only the ΔDS had a 5% level of significant difference in a two-tailed paired t-test (p = 0.012).

Discussion

1. Validity of the method

In the results for quiet standing, it was shown that bioelectrical impedance at low frequency changes with the standing load. Swelling levels under similar conditions are 1–2% obtained by Winkel with volume measurement (quiet standing for 30 min)\(^ {13} \), 1.2 % by Stick \textit{et al.} with high frequency impedance measurement (quiet standing for 20 min)\(^ {13} \) and 0.5–1% by Onishi (Report of Institute for Science of Labour) with leg circumference measurement (one foot standing for 30 min). Our result obtained with low frequency impedance measurement is 6.81%, which is about 3–5 times greater than the results of Winkel and Stick. The difference between our data and those of Winkel or Stick is that they are very close to the theoretical prediction as we mentioned concerning the theoretical analysis. The rate of change in leg circumference obtained in our experiment is 0.81%, and it is also near to the result obtained by Onishi, although we did not use a special device to maintain tape measure tension.

2. Effect of exercise

Leg exercise is theoretically effective in reducing swelling of the lower leg, because muscle contractions excite function of the musclevenuous pump and interstitial fluid should be removed\(^ {16} \). However, concerning this various results were reported. Winkel reported that a one minute walk was quite effective in keeping leg volume at the initial level\(^ {1} \), but Stick \textit{et al.} reported that repeated heel ups were entirely ineffective in swelling prevention\(^ {13} \). Our results for continuous walking showed a clear effect in preventing swelling, but the result of iterative exercise and standing showed that one minute walking on the spot was not so effective. The points of difference between these experiments are the types and duration of exercise. It is necessary to clarify these points to apply this method to the evaluation of the effect of exercise.

3. Subjective discomfort and standing load

The results for quiet standing and the iterative exercise and standing showed that between swelling and subjective discomfort there was a positive relationship, but the results for continuous walking showed a reverse relationship. Many factors might effect subjective discomfort, for example, muscle fatigue, joint compression, hemodynamics and mental stress, besides leg swelling\(^ {17–19} \). For example, the effect of muscle fatigue may be dominant in walking for long hours at a high pace, but mental stress may be dominant in monotonous standing jobs. In these cases, the relationship between the standing load and leg swelling will be dissociated, and it is hard to evaluate the standing load by leg swelling.
4. Further investigation

In this paper, we were able to partially clarify the effect of standing and exercise on impedance in the lower leg. It remains necessary to clarify the effect of standing, sitting and laying posture on leg swelling. It will be useful to evaluate the difference between the sitting and standing styles of working, and sitting and lying styles of resting.

It also remains necessary to clarify the daily pattern of leg swelling in order to precisely evaluate the daily standing load. Because workers work in various styles, leg swelling might increase or decrease while working. For this purpose, it is necessary to measure leg swelling repeatedly without disturbing the subject, and the method of impedance measurement is quite advantageous for this purpose.

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References

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立ち作業負担評価のためのインピーダンス測定法

立位で行う作業の負担評価のためのインピーダンス測定法について検討した。この方法は、下肢の電気的インピーダンスの変化を測定することによりその腫脹のレベルを評価するという方法である。本報告では、まず、他の下肢腫脹測定法との比較および測定条件の検討を電気的な数学モデルで行った。さらに得られた測定条件に基づいて実際に被験者に3種類の立位負荷を与えてインピーダンスを測定し、その妥当性を検討した。下肢体重变动測定・下肢周囲周長測定・インピーダンス測定の3種類の測定法を、円柱導電体とみなした下肢の腫脹が断面半径の変化で示されるという理論モデルにより比較検討した。その結果、インピーダンス法により測定される下肢腫脅の変化率は、下肢体重測定法とは同じであるが、下肢周囲周長測定法と比べると2倍の変化率を示すことがわかった。測定条件については生体組織の電気的等価回路を用いて解析を行った。その結果、インピーダンスの測定周波数は低いほうが高い場合よりも4倍程度大きな変化率を示すことが明らかとなった。従って、下肢体重変動測定法を用いれば、他の下肢腫脅測定法よりも高い検出力で下肢腫脅を測定しようことが判明した。次に、10名の男性被験者に対し、(1)静止直立(30分間)、(2)運動(30分間)、(3)連続歩行(速度1m/sで120分間)の3回繰り返し、(3)連続歩行(速度1m/sで120分間)の3種類の立位負荷を与え、下肢のインピーダンス・下肢周囲周長・下肢の自覚的不快感を測定した。インピーダンスは、測定を自動化した装置を試作し、4電極法により測定周波数5kHzで測定した。安静直立では、インピーダンスは時間とともに低下するパターンを示した。30分間でのインピーダンス変化率は6.8±4.54%（mean±SD）である。これは下肢体積測定法あるいは下肢周波数での下肢インピーダンス測定法による他の論文での変化率の3~5倍となっている。これは、生体組織の電気的等価回路によるモデル解析の結果に一致するものであり、下肢腫脙が下肢周波のインピーダンス測定で良好に捕らえられることが確認された。また、運動と直立の繰り返しのデータおよび連続歩行のデータより、運動や歩行でインピーダンスが上昇することが確認された。運動は下肢の筋繊維を作動させたため腫脅を顕著させると考えられている。今回の結果はこれに合致するものであるが、文献的には逆の結果も報告されている。運動の種類や持続時間が影響する可能性もあり、その評価に更に検討を要する考えられる。下肢の自覚的不快感については、安静直立及び運動と直立の繰り返しでは、インピーダンスでとらえ得る下肢腫脙に応じて自覚的不快感が増加するという結果が得られた。しかし、連続歩行では下肢腫脙は減っているのにかかわらず自覚的不快感は増大するという逆の結果となっていた。自覚的下肢不快感は下肢腫脙のみで決まるものではないので、このような結果になったのではないかと思われた。

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WORK-RELATED FACTORS OF LOW BACK PAIN AMONG NURSING AIDES IN NURSING HOMES FOR THE ELDERLY
Takashi FUJIMURA, Nobufumi YASUDA, and Hiroshi OHARA ………………………………………………………………………………… 89-98

老人ホーム介護職員における腰痛症の作業関連要因

藤村 隆，安田誠史，大原啓志

1991年12月に、高知県内の全部特別養護老人ホーム32施設およびそこで勤務する介護職員555名を対象に調査を行った。調査の目的は、介護職員の腰痛症とその入所者の日常生活動作（以下、ADL）における要介助との因果関係を明らかにする作業である。腰痛症の作業関連要因を調査するため、腰痛に関する質問票を介護職員に配布し、一方で、特別養護老人ホームの入所者の状況等に関する質問票を各施設の主任介護職員