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Reversal of Lower Limb Venous and Lymphatic Pooling by Passive Non-Invasive Calf Muscle Pump Stimulation

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Abstract—**Our preliminary data indicate that exogenous plantar micromechanical stimulation at 45 Hz applied at the plantar surface can prevent tachycardia and blood pressure depression associated with immobility, consistent with improvement in venous and lymphatic fluid return delivered by increased calf muscle activity. In this study, instantaneous beat-to-beat systolic blood pressure of thirty four healthy adult women participants (n=34; age range: 35-78 years) were assessed non-invasively using servo-controlled infra-red finger arterial plethysmography, for 30 minutes in the supine position, followed by 30 minutes in the seated position without plantar stimulation, and lastly for 30 minutes in the seated position with the application of a 45 Hz plantar stimulus (50µm, *p-p*). Thirty minutes of supine rest resulted in an average increase of 15 mmHg in systolic pressure. During the 30 minutes of upright sitting regimen, two distinct sub-populations were observed. One group (n=18; "hypotensives") experienced a depression of approximately 15 mmHg in systolic pressure, while the other group (n=16; "normotensives and hypertensives") experienced an elevation in the systolic pressure by approximately 8 mmHg. The subsequent 30 minute application of plantar stimulus reversed the pressure drop in hypotensives and elevated the systolic pressure by approximately 20 mmHg in all the subjects. Plantar-based exogenous micromechanical vibration may be an effective approach for reversal of blood pressure depression associated with the physical stress of immobility over a long term, consistent with enhanced venous and lymphatic fluid return delivered via improved calf muscle contractility.**

Keywords — **Venous Flow, Lymphatic Flow, Continuous Blood Pressure, Plantar Stimulation, Calf Muscle Pump**

I. Introduction

CALF skeletal muscle pump, a.k.a "*second heart*" activity is essential for the maintenance of venous and lymphatic circulatory adequacy during upright posture and activity [1]. The volume of the peripheral flows is greatly influenced by the increased hydrostatic forces created by gravity when an individual is upright. For example, up to 20% of serum fluid leaves the vascular system through extravasation within 30 minutes of attaining upright stance, as shown in Figure 1 [2]. This fluid largely accumulates in the venous and interstitial spaces of the lower limbs unless taken up by the venous and lymphatic systems. Inadequate fluid return, therefore, results in substantially increased peripheral pressures. High tissue pressures serve to inhibit extravasation from the vascular supply with a corresponding loss of nutrient delivery to the dependent tissues. Exposure to elevated hydrostatic pressures is transmitted to the capillary bed where the balance of filtration favors transudation into the extracellular fluid resulting in transient edema. Chronic, sustained venous hypertension resulting due to the diminished effectiveness of the muscle pump system is closely associated with several pathological consequences including short-term ones such as edema, blood stasis, orthostatic hypotension, and tachycardia, and chronic conditions such as peripheral reflux diseases [3,4,5], depression [6], chronic fatigue [7,8,9], dementia [10,11], Alzheimer's disease [12,13], and more recently, heart failure [14].

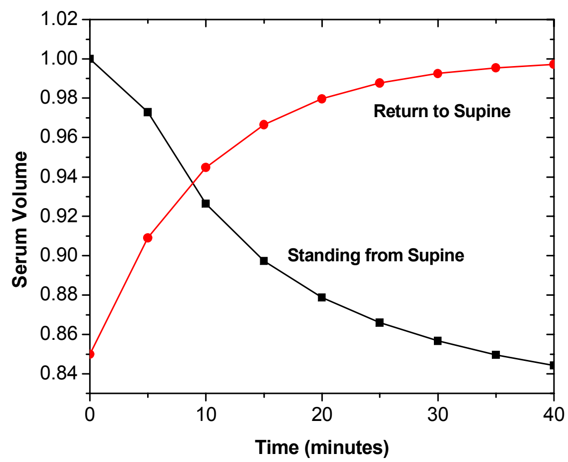

Figure 1: Redistribution of body fluid following transitions from supine to upright and upright to supine in young healthy adults. 15-20% of serum volume is lost due to extravasation from the capillaries due to the large, gravity generated, hydrostatic pressures existing in the vascular system of the lower limbs during upright posture. Absence of adequate skeletal muscle pumping results in substantially higher fluid pooling in the lower extremities with concomitant hypotension, tachycardia, and blood stasis. (After Hagan, et al. 1978).

In our recent studies investigating the influence of upright posture on blood pressure and interstitial fluid flows, we observed that plantar micromechanical stimulation was able to normalize blood pressures [15] and flows [16] in upright, immobile individuals, by activating the calf muscle pump. We hypothesized, therefore, that similarly plantar stimulation may serve as an effective means to reverse peripheral fluid accumulation in individuals during quiet sitting, particularly

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those with inadequate compensatory mechanisms, thereby enhancing cardiovascular function in these afflicted individuals.

To address this hypothesis, we investigated continuous blood pressure responses to quiet sitting and the extent to which plantar micromechanical stimulation could reverse fluid pooling and correspondingly, the deleterious cardiovascular responses to this stress. Because orthostatic intolerance is more common in women that progresses with aging, we focused our pilot investigation on an adult female population.

II. METHODS AND MATERIALS

A. Approval

The procedures in this study were conducted in accordance with the standards set by the Declaration of Helsinki (2000). The study protocol was approved by the Institutional Human Subjects Research Review Board at Binghamton University (State University of New York). After a detailed verbal explanation of the study protocol, written informed consent was obtained from each participant prior to the session.

B. Subjects and Study Design

Non-pregnant women between the ages of 35 and 80 who were capable of understanding and providing informed consent and following the study protocol were recruited for the study. The entrance criteria for this clinical study were healthy adult women with no current fractures, peripheral vascular disease, or systemic illness, and capable of providing informed consent. During screening, subjects' age, height, weight, BMI, physical activity, general health, and medical status were ascertained.

C. Laboratory Evaluation

A servo-controlled, infra-red plethysmographic, beat-to-beat, automated finger arterial blood pressure monitoring system was used for continuous cardiovascular monitoring (Portapres Model 2, TNO-BMI, Amsterdam, The Netherlands). Calf muscle pump stimulation was obtained by means of a plantar vibration device that has been evaluated by the FDA and is a non-significant risk device, as defined by their Investigational Device Exemption Regulation. The device consists of a rectangular platform constructed with a polymeric top plate on which an individual places his/her feet for treatment (Figure 2). The platform is a spring supported resonance-based structure and delivers 45 Hz frequency at an amplitude of 50 µm, peak-to-peak.

D. Protocol

The subjects were instrumented with the finger cuff and the height correction unit of the Portapres blood pressure monitoring unit. A remote controllable power recliner was utilized to lower the subjects into the supine position and raise them to the seated position without muscular effort. The overall duration of each session was 90 minutes. Following a 30 minute equilibration in the supine position, each subject completed two separate, sequential 30 minute exposures. These two conditions included quiet sitting for 30 minutes with the subjects' feet on the unactivated plantar vibration platform, followed by quiet sitting for 30 minutes with the application of plantar stimulation. Systolic blood pressure data acquired continuously throughout the during the seated and seated with plantar stimulation conditions.

Figure 2: Plantar stimulation device utilized in the seated position. A resonance based design allows a small electromagnetic actuator to provide the 50 µm displacement to the plantar surface of subjects. The lack of any direct attachment to the patient allows convenient use.

E. Data Acquisition and Analysis

During post-processing, the beat-to-data were resampled providing a consistent 1 Hz sampling frequency for all subjects, allowing the datasets to be averaged for further analysis.

III. RESULTS

Thirty four (N=34) white adult women were screened for this study. The mean population age was 53.8 ± 1.9 years with an average height of 164.5 ± 1.9 cm and a mean BMI of 26.7 ± 0.7 kg/cm^2. In all of the cases, the subjects reported a 'pleasant' stimulus sensation. No experimental complications were observed in any of the trial in this investigation.

The changes in systolic pressure were not dependent on subject age, height, weight, or BMI. During the first 30 minutes of supine rest, there was an overall average increase of 17 mmHg in systolic pressure. The systolic pressure dropped approximately 15 mmHg during the subsequent 30 minute upright sitting regime in a subset of hypotensive population containing 18 subjects. The rest of the 16 subjects, containing a mixture of normotensives and hypertensives, had an average increase of up to 8 mmHg in their systolic pressure. Upon application of 45 Hz plantar stimulus, the systolic pressure responses were completely nullified and experienced a reversal of up to +15 mmHg in the hypotensive population (Figure 3).

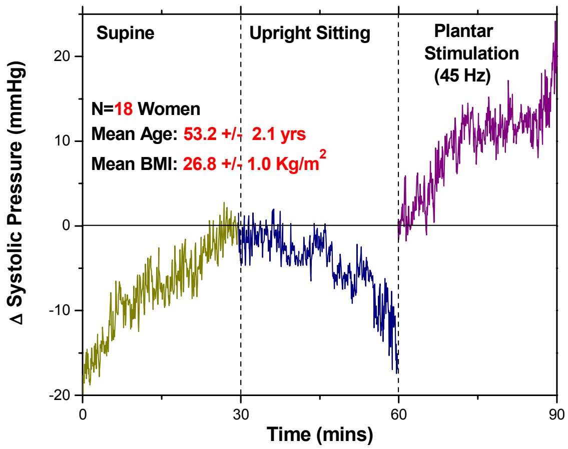

Figure 3: Systolic blood pressure response for 18 hypotensive subjects over a 90 minute protocol period. The first 30 minutes represent subjects in the supine position, the second 30 minute duration represents an upright sitting regime with the subjects' feet placed on an unactivated plantar stimulation platform, and the last 30 minutes represent upright sitting with 45 Hz plantar stimulation. Thirty minutes of quiet upright sitting resulted in significant drop in systolic pressure (-15 mmHg) after 30 minutes supine rest (+20 mmHg). Plantar stimulation applied for the last 30 minutes completely reversed and elevated the systolic pressure.

IV. Discussion

Quiet sitting is not normally thought of as a significant orthostatic stress. Sitting upright still leads to the translocation of thoracic blood volume into the lower extremities, requiring both peripheral venoconstriction and skeletal muscle pump activity to maintain normal systemic blood pressure and heart rate, such that lack of either or both of these adaptive processes can lead to resting tachycardia. Correspondingly, over one-half of the adult women we tested in our study developed a substantial drop in systolic blood pressure (~15 mmHg). The cardiac response data for this group, therefore, leads us to suggest that, for a significant fraction of adult women (55%), the immobility associated with quiet sitting represents a significant orthostatic challenge with peripheral regulatory mechanisms incapable of providing full compensation.

While these results are supportive of our initial hypothesis, certain aspects of the experimental design limit the interpretation of these results. Specifically, we have only looked at this response in women, knowing to what extent men exhibit similar responses would be an important extension of this work. Similarly, extending recordings beyond 30 minutes would provide knowledge of the ability of plantar vibration to maintain normal heart rate and blood pressure in response to a sustained seated activity, such as encountered during long distance travel. Further studies will be required to address these issues.

V. Conclusion

The results support the hypothesis that plantar-based calf muscle pump stimulation can largely eliminate the effects of the cardiovascular stress of quiet sitting. We suggest that these observations may have significant implications given the extended durations over which many Americans, especially the elderly population, remain seated and relatively immobile during the course of their day in the workplace, following passive entertainment options, and during long-distance travel.

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