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A Hemodynamic Study of Popliteal Vein Blood Flow: The Effect of Bed Rest and Electrically Elicited Calf Muscle Contractions

Barry J. Broderick, *Member, IEEE,* David E. O'Briain, Paul P. Breen, *Member, IEEE,*
Stephen R. Kearns and Gearóid ÓLaighin, *Senior Member, IEEE*

Abstract—**Venous stasis, due to lack of activation of the calf muscle pump of postoperative patients, can result in the development of a thrombus which, in turn, can lead to a potentially fatal pulmonary embolism. The presented study investigates the effects that four hours of bed rest has on the lower limb hemodynamics of healthy subjects and, to what extent electrically elicited contractions of the calf muscles can alleviate these effects. Results indicated that the non-stimulated group experienced a decline in popliteal venous blood flow of approximately 45 % and a 10 % decrease in heart rate. The stimulated group maintained a higher venous blood flow and heart rate.**

The results suggest that even short periods of bed rest can significantly reduce lower limb blood flow which could have implications for DVT development in post-operative patients. Electrically elicited calf muscle contractions significantly improves lower limb blood flow and can alleviate the debilitating effects of bed rest.

I. Introduction

Venous thromboembolism (VTE) remains a serious medical concern in hospitalized patients, causing morbidity and mortality [1-3]. VTE includes the formation of deep venous thrombosis (DVT), which is the product of activation of coagulation in a deep vein, and pulmonary embolism (PE) which arises when some or all of the DVT is dislodged and travels to the lungs [3]. Mortality rates associated with PE have been reported to be as high as 17.4 % [4]. Thrombi located in the proximal veins are more likely to result in a PE [2]. Incident rates of DVT in general surgical patients has been reported to be 10 to 40 % [5], while the rate of DVT development following orthopaedic surgery has been reported to be 40 to 60 % [6]. Post-thrombotic syndrome, which is characterized by pain, swelling and venous ulceration, can occur secondary to DVT [7, 8]. This is due to venous hypertension resulting from the destruction of venous valves or due to abnormal micro-circulation.

Three factors are responsible for the formation of DVT (referred to as Virchow's triad):

- damage to the vessel wall, caused by trauma arising from shear stress or hypertension
- changes in blood constituents or hypercoagulability
- venous pooling or stasis, caused by alterations in normal blood flow.

In the case of lower limb surgery, anaesthesia, circulation interruption, bed rest and the alteration in the blood constituents due to the inflammation inherently associated with surgery, create an ideal situation for the development of DVT. Changes in blood constituents can be controlled using medication [2]. Venous stasis can be reduced through the use of compression stockings and pneumatic compression [10, 11]. These are the mainstay of conservative DVT preventative methodologies. However, Arnold et al. point out that many indicated DVTs could have been prevented had prophylaxis been administered adequately, despite their availability. The authors noted that omission of prophylaxis was the most common of these inadequacies [1].

Lack of activation of the calf muscle pump gives rise to pooling of blood in the lower leg. It is clear that post-operative rest poses an increased risk factor for DVT development, as a consequence. However, despite this knowledge, little data exists as to the extent bed rest recovery affects lower limb blood flow. The aim of this study was to evaluate the effect of bed rest on lower limb venous hemodynamics and to determine to what extent prophylaxis, in the form of neuromuscular electrical stimulation (NMES) induced calf muscle contractions, alleviates these effects. NMES has demonstrated positive hemodynamic responses in healthy subjects and patients suffering from chronic venous disease [9, 12]. NMES has reported benefits over pneumatic compression devices [13].

II. Methods

A. Participants

Ten healthy subjects were recruited for this study from the National University of Ireland, Galway. Six male and four female subjects took part who had a median age of 24 (range: 21–36 years), height 173 cm (170–184 cm), weight 71.9 kg (70.45–91.2 kg), BMI 23.8 kg/m² (21.9–26.9 kg/m²). A member of the investigation team initially examined the subjects to ensure they satisfied the inclusion and exclusion

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B. J. Broderick is with Electrical & Electronic Engineering, National University of Ireland Galway, University Road, Galway, Ireland and the Bioelectronics Research Cluster, National Centre for Biomedical Engineering Science, National University of Ireland Galway, University Road, Galway, Ireland (phone: +353-91-493126; fax: +353-91-494511; e-mail: b.broderick2@nuigalway.ie).

P. P. Breen and G. ÓLaighin are with Electrical & Electronic Engineering, National University of Ireland Galway, University Road, Galway, Ireland and the Bioelectronics Research Cluster, National Centre for Biomedical Engineering Science, National University of Ireland Galway, University Road, Galway, Ireland.

D. E. O'Briain and S. R. Kearns are with the Department of Surgery, National University of Ireland Galway, University Road, Galway, Ireland.

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criteria. The exclusion criteria was as follows: history of heart or respiratory problems, pregnancy, current use of oral contraceptive pill, current smoker, history of peripheral vascular disease or previous thromboembolic event, history of leg fractures and/or presence of metal implants in the leg and long distance travel within one week prior to study All subjects gave written consent to take part in the study. Ethical approval was granted by the National University of Ireland, Galway Research Ethics Committee.

B. Resting Protocol

All subjects (n=10) were asked to remain lying in a bed for the four hour duration of the study (resting group). The study took place in the Clinical Skills Laboratory at the National University of Ireland, Galway, a simulated hospital ward environment. The head of the bed was raised to a comfortable position to allow subjects to read or work on a laptop throughout the study. Each subject wore a pair shorts and no foot wear to allow easy access to measurement sites. The resting popliteal vein blood flow velocity, cross-sectional area, volume flow and heart rate of each subject was assessed at the start, middle and end of the study (two hour increments).

C. Electrical Stimulation Protocol

On a separate day, subjects were asked to repeat the previous protocol. However, this time neuromuscular electrical stimulation was applied to the calf muscles in order to increase popliteal vein blood flow through activation of the calf muscle pump (stimulation group). Stimulation was applied alternatively to each muscle with 30 seconds rest between contractions. Stimulation amplitudes were set by determining the maximum level tolerated by each participant for each muscle group before starting the protocol. This yielded stimulation amplitudes of 29.18 ± 4.2V. Electrical stimulation was facilitated through the use of 5x5cm PALS self-adhesive hypo-allergenic skin surface electrodes (Nidd Valley Medical Limited, England) placed over the motor points of the calf muscles on the lower leg.

Electrical stimulation was applied using the Duo-STIM muscle stimulator [14]. The stimulator was programmed to provide a pulse width of 350 μs, an inter-pulse interval of 100 μs, a frequency of 36 Hz, a contraction time of 1.2 s, a ramp up time of 500 ms and ramp down time of 300 ms. The stimulation parameters were selected to achieve maximum blood flow while ensuring subject comfort and were based on the stimulation guidelines described by Baker et al. [15].

D. Duplex Scanning

Duplex Doppler ultrasound was used to monitor the subjects' lower limb hemodynamics using a 4–8 MHz linear transducer (LOGIQ e, GE Medical Systems). All measurements were performed by a single examiner. Blood flow measurements were taken from the popliteal vein and artery at the lateral aspect of the knee, after the sapheno-popliteal junction. All measurements were taken from the right leg. Three measurements were taken per parameter and the average value used for analyses. Peak venous velocity, vein cross sectional area and venous volume flow measurements were recorded from the popliteal vein. Heart rate was measured from the popliteal artery. Average blood flow velocity was obtained by analyzing the Doppler pulse waveform and calculating the average of the velocity waveform over a 4 second window. Venous volume was calculated by multiplying the average blood flow velocity by the cross-sectional area of the popliteal vein. Only baseline blood flow measurements were recorded for the resting group. The measurement set for the stimulation group involved a baseline (recovery flow) measurement, followed by an NMES blood flow measurement at each time point.

E. Statistical Analysis

A repeated measures ANOVA was used in all analyses (SPSS). Any violations to the assumption of sphericity were corrected using the Huynh-Feldt correction for estimates greater than 0.75 or the Greenhouse-Geisser correction for estimates less than 0.75. Relationships between variables were determined using Peason's correlation coefficient. A p value of < 0.05 was considered statistically significant.

III. RESULTS

A. Resting Flow Versus Recovery Flow

Time had no significant effect on peak velocity measurements for either group, $p = 0.1$. However, the normalized volume flow of the resting group was significantly affected by time, $p < 0.05$ (Fig. 1). Volume flow reduced by ~37 % after two hours, $p < 0.01$, and by ~45 % after the four hours, $p < 0.01$. Normalized recovery volume flow of the stimulated group remained constant throughout the study, $p = 0.18$.

B. Heart Rate of Resting Group Versus Stimulated Group

Heart rate was significantly affected by time in the resting group, $p < 0.01$ (Fig. 2). There was an average drop in heart rate of ~12 % from baseline at the two hour mark, $p < 0.01$. Heart rate increased slightly to ~10 % of baseline at the four hour mark, $p < 0.05$. No changes in the heart rate measurements of the stimulation group were observed with respect to time, $p = 0.08$. There was a significant relationship between venous volume flow and heart rate in the resting group, $r = 0.99$, $p < 0.05$.

C. Stimulated Peak Venous Velocities

Fig. 3 shows the stimulated peak venous velocity measurements of the stimulation group compared to the unstimulated resting group. The stimulation group was associated with significantly higher peak venous velocities than the resting group, $p < 0.001$. The stimulation group experienced ~573 % increase in flow velocity with respect to resting. There was no stage effect for the stimulated peak venous velocity measurements, $p = 0.63$.

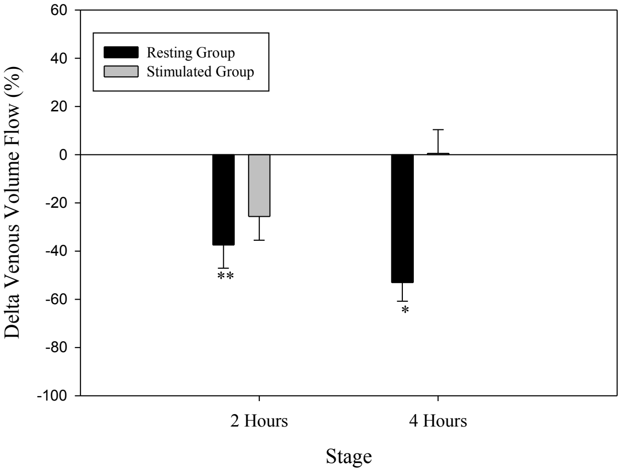

Fig. 1. Percentage changes in venous volume flow at two hours and four hours of bed-rest from baseline in the resting and stimulated group.
* $P < 0.05$ when compared to baseline, ** $p < 0.001$ when compared to baseline.

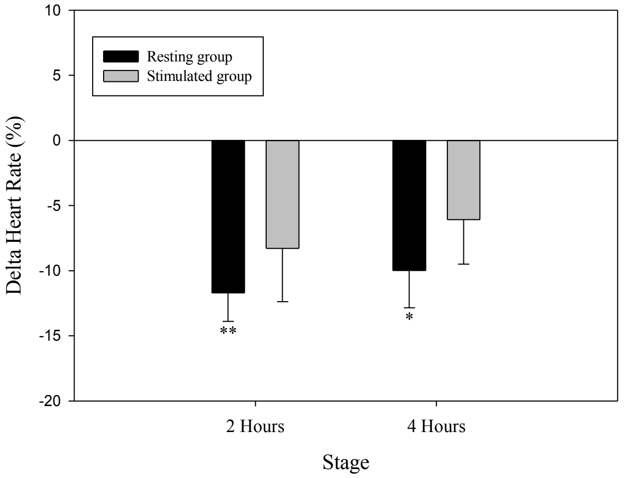

Fig. 2. Percentage changes in heart rate at two hours and four hours of bed-rest from baseline in the resting group and stimulated group.
* $P < 0.05$ when compared to baseline, ** $p < 0.001$ when compared to baseline.

D. Stimulated Volume Flow

Fig. 4 shows the stimulated venous volume flow of the stimulation group compared to the unstimulated resting group. The stimulation group was also associated with significantly greater volume flow than the resting group, $p < 0.001$. The stimulation group experienced ~211 % increase in volume flow with respect to resting. There was no significant stage effect for the stimulated venous volume flow measurements, $p = 0.97$.

IV. DISCUSSION

Controversy exists over the use of peak venous velocity as an indicator of venous blood flow. Despite peak venous velocity being the blood flow parameter typically reported in literature as a measure of mechanical DVT prophylaxis efficacy, Morris and Woodcock found no evidence that a higher peak velocity yields lower DVT rates [11]. The reduction in popliteal blood flow in the present study was only detected by a drop in venous volume flow. As the focus was on prevention of hemostasis, peak venous velocity measurements were of little hemodynamic importance during this study.

These data demonstrate that after four hours of bed rest, blood flow in the popliteal vein reduced significantly by approximately 46 %. This reduction in popliteal vein flow would result in a gradual drop in venous return. The correlation between venous volume flow and heart rate was expected, as the resting position would reduce the metabolic demand of the leg muscles due to the lack of contraction and hence, reduce heart rate.

The reduction in venous flow would have little effect on the healthy subject group monitored, who have no DVT risk factors. However, this could have significant implications for DVT development in post-operative patients, even those discharged from hospital on the day of surgery. Squizzato and Venco point out that pharmacological thromboprophylaxis is not recommended for this patient group as the risk of major bleeding may exceed the risk of thrombotic complications [16]. For these reasons, the use of NMES prophylaxis may be preferable.

NMES is the application of an electrical stimulus to motor points in the body using electrodes placed on the surface of the skin to elicit a muscular contraction. NMES applied to the calf muscles facilitates venous return by activating the skeletal muscle pump. NMES may be more effective than compression therapies as a DVT preventative measure due to its ability to empty the deep venous sinuses completely, a common site for DVT formation [13].

The findings of this study suggest that NMES was capable of reversing the decline in resting popliteal blood flow due to bed rest. The stimulus pulse, delivered once every minute, caused the between stimulus "recovery" venous volume flow to remain constant throughout the four hour bed rest period for the stimulated group. In comparison, the resting group experienced a 46 % decrease in flow. The stimulus pulses themselves elicited peak venous velocities and volumes that far exceeded baseline (approximately 573 % increase in peak venous velocity and approximately 211 % increase in volume flow).

We also observed that the NMES groups maintained a higher heart rate throughout the study. With high venous return, the cardiac muscle is stretched and therefore contracts more powerfully. Increased contractility with no increase in after-load will result in increased stroke volume. The increased metabolic demand probably leads to a more rapid decrease in aortic pressure due to blood heading to the muscles in use. This would mean the baroreceptors are less stimulated and do not slow heart rate as much in the stimulation group compared to the resting group. NMES elicited calf muscle contractions would also have the effect

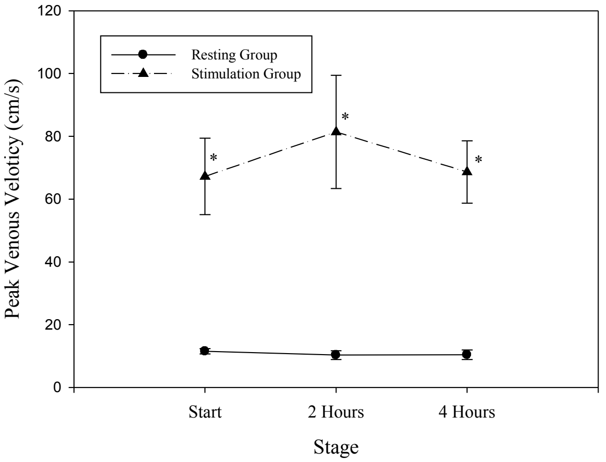

Fig. 3. Peak venous velocity (cm/s) measured at the start and after two and four hours of bed-rest. * $P < 0.001$ when compared to baseline at each stage.

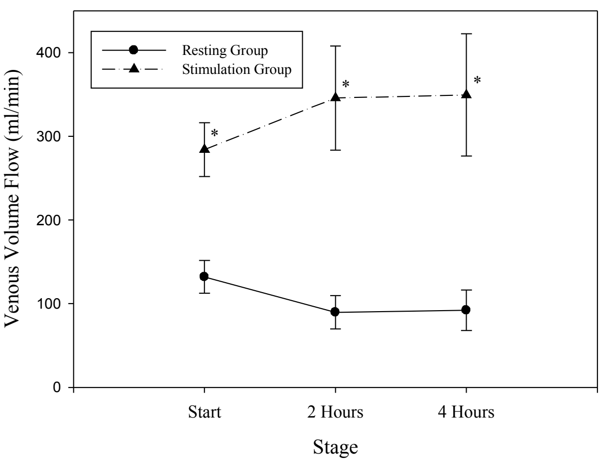

Fig. 4. Venous volume flow (ml/min) measured at the start and after two and four hours of bed-rest. * $P < 0.001$ when compared to baseline at each stage.

of stimulating the sympathetic nervous system which would lead to increased heart rate and further increase in contractility of the heart muscle.

V. CONCLUSION

The results of this study suggest that even short periods of bed rest can significantly reduce lower limb blood flow. This could have implications for DVT development in post-operative patients and highlights the importance of formal risk assessment for every hospitalized patient. NMES significantly improves lower limb blood flow and can alleviate the debilitating effects of bed rest.

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