

Hemodynamic effect of intermittent pneumatic compression and the position of the body

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Purpose: The purpose of this study was to investigate the three likely mechanisms of intermittent pneumatic compression (IPC) in deep vein thrombosis prophylaxis (increased volume flow, increased flow velocity, and acceleration of flow) and to do this in a variety of positions, in different venous segments, and with the stimulus of three different compression garments.

Methods: In 12 healthy volunteers, three types of compression cuffs were used: foot, calf, and calf + thigh. The foot was compressed with 80 mm Hg, and the calf and thigh with 40 mm Hg. Duplex ultrasound scan was performed before and during the compression in the horizontal, 15-degree head-down, and 15-degree head-up positions. The common femoral, greater saphenous, profunda femoral, superficial femoral, and popliteal veins were examined.

Results: In comparison with the horizontal position, the 15-degree head-down position was associated with an increase of volume flow and velocities and the head-up position was associated with decreased flow and velocities in the deep veins. The application of IPC caused significant increases in velocities and volume flow in all venous segments. The lowest increase in velocities and volume flow in the deep veins was observed with the subjects in the head-down position, and in the two other positions, the increases were greater and similar to each other. IPC caused a much more prominent increase in flow velocities and volume flow in deep veins compared with simple elevation of the legs.

Conclusion: IPC produces significant increases of venous flow volume and flow velocity and acceleration of flow. This is true whether the limbs are elevated, horizontal, or dependent. Segmental flow changes vary with the position of the patient and the compression garment used. Foot compression increases volume flow and velocity primarily in the popliteal vein. Calf compression provides maximal increases of volume flow and flow velocity through the deep veins. (J Vasc Surg 2003;37:137-42.)

Venous stasis is considered to be a major contributing factor of thromboembolic events in patients during prolonged bed stay, especially when the lower extremities are immobilized. Mechanical prevention of the venous stasis is one of the major prophylactic measures in this group of patients. Elevation of the lower extremities was the first preventive measure against deep vein thrombosis (DVT), acting with increase of venous return from the extremity. Introduction of intermittent pneumatic compression (IPC) of the legs has not changed this recommendation. We are not aware of any study designed to compare the effect of IPC versus leg elevation on the venous blood flow in the lower extremities. The influence of the position of the extremity on the efficacy of IPC also has not been studied sufficiently.¹

Proponents of IPC emphasize two possible physiologic effects associated with its use: increase of the venous flow²⁻⁴ and activation of the fibrinolytic system.^{5,6} The latter is most likely caused by changes in sheer stress on the endo-

thelial surface, and therefore, it is directly related to flow velocity and to acceleration of the flow during IPC.⁴

Thus, the three likely mechanisms for the effectiveness of IPC in DVT prophylaxis are increased volume flow, increased flow velocity, and increased shear stress from acceleration of flow from the pump. Each of these parameters can vary significantly in individual venous segments, without affecting the total return from extremity. The increase of velocities in the common femoral vein (CFV), for example, can coexist with stasis in the profunda femoris vein (PFV) or even in the superficial femoral vein (SFV), when the greater saphenous vein (GSV) serves as the major source of outflow. Despite this, none of the published studies of hemodynamic effects of IPC provide information on changes in individual venous segments. The purpose of this study was to investigate each of these parameters in the normal individual in a variety of positions, in each of the segments of the venous tree, and with the stimulus of different sites of pump placement.

MATERIAL AND METHODS

Twelve healthy volunteers, five men and seven women, age 19 to 45 years (mean, 28 years) participated in this study. None of the participants had a history of DVT, symptoms of venous disease, or evidence of lower extremity arterial disease. All participants signed an informed consent approved by the Straub Clinic and Hospital Institutional Review Board before their involvement in the study.

The pneumatic compressive device used, the ALP Pump System (Healthcare Service and Supply, Tustin, Cal-

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Table I. Segmental volume flow in different positions of body

Position	Segmental volume flow (mL/s; mean \pm standard error)				
	CFV	SFV	PFV	Popliteal vein	GSV
Horizontal	16.1 \pm 0.5	6.9 \pm 0.8	5.3 \pm 0.4	3.8 \pm .6	3.9 \pm 0.3
Head-down	20.1 \pm 0.8*	10.8 \pm 1.2*	5.5 \pm 0.5	3.5 \pm .5	3.8 \pm 0.3
Head-up	14.4 \pm 0.4	6.1 \pm 0.4	4.2 \pm 0.2*	3.2 \pm .7	3.5 \pm 0.3
P value	<.001	<.001	.049	.76	.59

Mean values (n = 12) of volume flow without application of IPC are listed for each studied venous segment. *P* values listed for one-way analysis of variance comparison of three positions.

*Values significantly different from those at other positions (Tukey post hoc test).

if), had an affixed 1-minute cycle consisting of a 12-second inflation and a 48-second deflation interval. Three types of compression garments were used: foot, calf, and simultaneously inflated calf + thigh. All were single-chambered garments. The foot was compressed with 80 mm Hg \pm 5 mm Hg, and the calf and thigh with 40 mm Hg \pm 5 mm Hg, which were the optimal pressures suggested by the manufacturer.

Duplex ultrasound scan examination (ATL-Ultramark 9, Advanced Tech Laboratory, Bothell, Wash) of the lower extremity venous system was performed in each volunteer to confirm the absence of abnormalities. Then, each subject was placed in the supine position for 5 minutes to establish equilibrium and to obtain baseline flow characteristics. During the experiments, each subject was observed in the horizontal, 15-degree head-down, and 15-degree head-up positions, changed randomly. After each position change, 5 minutes of equilibration time were permitted before the measurements were taken. On completion of the measurements in each position, participants were placed in the horizontal position, and the flow velocities were allowed to return to their baseline values before the experiment continued. The flow measurements were repeated three times at the baseline and during application of IPC in each position and with each of the three randomly applied pneumatic compression cuffs.

The CFV, the GSV 5 cm distal to the saphenofemoral junction, the PFV 1 cm distal to the confluence with the SFV, the SFV at 3 to 5 cm from the confluence with the PFV, and the popliteal vein were examined. After identification of the segment, the shape of the vein was confirmed to be close to circular in the transverse plane to achieve more reliable measurements of the flow.⁷

Then, the transducer was returned to the longitudinal position for the rest of the examination. All measurements were performed with the optimized setting described previously.⁸

The visual signals with the ATL-Ultramark 9 were recorded on VHS videotape for analysis. Recordings were performed during three flow cycles, with the frame rate of 30 frames/s, and then printed and analyzed. All measurements were performed with a planimeter/digitizer (LASICO series 1282, LASICO, Los Angeles, Calif).

For the purpose of cross-sectional area calculations, the cross-section of the vein was assumed to be circular. De-

tailed description of volume flow calculation has been published elsewhere.⁸

For the baseline values, the mean peak velocity (MPV) was defined as the mean of three highest peak velocities. For the compression cycle, the mean of highest velocities during the three compression cycles was used. Volume flow was calculated from time velocity integral for complete 1-minute compression cycle (the mean of three cycles) and for the same time at baseline.

Because maximal values of velocities during IPC depend on the baseline values, relative increase of velocity (MPV during IPC over baseline MPV value) was reported as an outcome variable. In this study, the same IPC device was used. The time of the garment inflation was constant (12 seconds). Therefore, the acceleration of the flow was directly and linearly related to velocity increase. In the pilot study of five extremities, we confirmed that the flow acceleration time (from the beginning of acceleration to the point of maximal velocity) was constant in all three positions and with each of the three types of garment.

Descriptive statistics, paired *t* test, and repeated measures analysis of variance were used with SPSS 10.1 statistical software (SPSS Inc, Chicago, Ill). Statistical significance was set at a *P* value of less than .05.

RESULTS

There were differences in baseline values of segmental velocities and volume flow (measured before IPC application) in different positions of the body. The 15-degree head-down position was associated with greater baseline volume flow in the CFV and SFV compared with the horizontal position. The head-up position was associated with lower flow in the CFV, the SFV, and the PFV compared with the head-down position (Table I). The baseline MPV showed the same trend as the volume flow. With the exception of the GSV, however, these velocity differences did not reach statistical significance (Table II).

The application of IPC caused significant increases in velocities and volume flow in all venous segments. The magnitude of this increase depended on the position of the body and on the type of compression garment. The lowest increase in velocities and volume flow in the deep veins was observed with the subjects in the head-down position, and in the two other positions, the increases were almost the same (Tables III and IV).

Table II. MPV in different positions of body

Position	MPV (cm/s; mean ± standard error)				
	CFV	SFV	PFV	Popliteal vein	GSV
Horizontal	27.1 ± 1.7	24.9 ± 2.6	20.6 ± 1.7	7.1 ± .8	16.9 ± 1.2
Head-down	30.4 ± 2.2	31.1 ± 2.7	21.6 ± 1.0	7.4 ± 1.1	19.3 ± 1.3
Head-up	26.0 ± 1.7	23.5 ± 2.0	17.2 ± 1.0	6.4 ± 1.1	14.2 ± 1.1
P value	.247	.073	.081	.75	.016

Mean values (n = 12) of MPV without application of IPC are listed for each studied venous segment. P values listed for one-way analysis of variance comparison of three positions.

Table III. MPV increase in venous segments during IPC

Position	Garment	MPV increase (mean ± standard error)				
		CFV	SFV	PFV	PV	GSV
Horizontal	Foot	1.7 ± 0.2	1.4 ± 0.1	1.4 ± 0.2	2.9 ± 0.3*	1.1 ± 0.2
	Calf	1.4 ± 0.1	2.6 ± 0.5	2.0 ± 0.8	7.9 ± 1.6	0.9 ± 0.2
	Calf + thigh	1.7 ± 0.1	2.7 ± 0.4	1.7 ± 0.2	6.2 ± 1.6	2.2 ± 0.3*
	P value	.3	.04	.62	<.001	.001
Head-down	Foot	1.1 ± 0.04	1.3 ± 0.04*	1.4 ± 0.8	2.5 ± 0.3*	1.3 ± 0.1
	Calf	1.2 ± 0.1	1.9 ± 0.2	1.6 ± 0.3	5.1 ± 1.1	1.5 ± 0.2
	Calf + thigh	1.8 ± 0.2*	2.0 ± 0.2	1.4 ± 0.5	5.4 ± 3.4	1.9 ± 0.4
	P value	.002	.006	.6	.004	.3
Head-up	Foot	1.3 ± 0.04	1.4 ± 0.1*	1.1 ± 0.1	3.14 ± 0.3*	1.4 ± 0.1*
	Calf	1.6 ± 0.1	3.5 ± 0.5	1.8 ± 0.3	11.5 ± 4.1	2.5 ± 0.4
	Calf + thigh	1.9 ± 0.3	3.1 ± 0.3	2.0 ± 0.3	6.0 ± 1.3	3.0 ± 0.7
	P value	.1	.0001	.06	.001	.06
Difference between positions	P value (foot)	.02	.14	.14	.3	.2
	P value (calf)	.01	.03	.9	.3	.0005
	P value (calf + thigh)	.9	.049	.2	.9	.3

Increase is defined as ratio of MPV during IPC over baseline MPV value in each extremity in each position. Mean values (n = 12) are listed for each compression garment used in each position of body. P values listed for one-way analysis of variance comparison of three garments.

*Values significantly different from those for other garments (Tukey post hoc test). Difference between positions was determined with two-way analysis of variance separately for each venous segment.

Foot compression caused lesser increases in velocities and volume flow compared with the other two types of garments. Compared with the other segments, the popliteal vein showed a much higher increase of flow and MPV when the foot garment was used, with a three-fold increase in the head-up position and more than a two-fold increase in the head-down position.

Calf compression was associated with the highest augmentation of volume flow and MPV in the popliteal vein, particularly in the head-up position. The effect of calf + thigh compression on hemodynamics in deep veins was not significantly different from calf compression alone, with the exception of the head-down position, in which the CFV showed higher MPV and volume flow increases.

Although elevation of the legs was associated with augmentation of the flow in deep veins of the thigh, the application of IPC caused a much more prominent increase in flow velocities and volume flow. MPVs were significantly higher during pneumatic compression than during elevation of the legs (Table V). Unlike leg elevation, IPC caused velocities to increase in popliteal veins and GSVs.

The volume flow through the deep veins of the thigh (SFV and PFV) was significantly higher during IPC than

during leg elevation (Table VI). The difference in volume flow through GSV between leg elevation and IPC was also statistically significant, however of much less magnitude. Volume flow in the popliteal vein showed a dramatic increase during IPC with values on average five times higher compared with those during leg elevation.

DISCUSSION

Venous stasis is generally understood as decreased flow in the veins. However, more detailed hemodynamic characteristics are needed to estimate the effect of the prophylactic devices, such as IPC. This effect has been inferred in the literature by increasing flow velocity in the CFV.⁹ It has not been investigated, however, whether this change in the velocity is from increase of volume flow or from decrease in vein diameter and whether this increase is from increased flow in deep veins or in the GSV or in both.

Different hemodynamic parameters have been studied in various reports of the application of different IPC devices,^{2-4,9,10} but their separate roles in DVT prevention have never been addressed. The exact hemodynamic goal of the external compression is not clear. It could be the increase of volume flow, or increase of mean flow velocity, or initiation

Table IV. Mean volume flow increase in venous segments during IPC

Position	Garment	Volume flow increase (mean \pm standard error)				
		CFV	SFV	PFV	Popliteal Vein	GSV
Horizontal	Foot	1.5 \pm 0.1	1.6 \pm 0.2	1.5 \pm 0.2	2.7 \pm 0.3*	0.9 \pm 0.1
	Calf	1.5 \pm 0.1	2.5 \pm 0.7	1.5 \pm 0.4	4.4 \pm 0.8	0.8 \pm 0.2
	Calf + thigh	1.8 \pm 0.2	2.5 \pm 0.4	1.4 \pm 0.1	5.6 \pm 1.0	1.8 \pm 0.1*
	P value	.13	.25	.97	.002	<.001
Head-down	Foot	1.2 \pm 0.1	1.3 \pm 0.1	1.5 \pm 0.1	2.5 \pm 0.3	1.3 \pm 0.1
	Calf	1.3 \pm 0.1	1.4 \pm 0.1	1.5 \pm 0.2	4.2 \pm 1.1	1.4 \pm 0.2
	Calf + thigh	1.8 \pm 0.3*	1.7 \pm 0.2	1.5 \pm 0.1	3.4 \pm 0.6	1.5 \pm 0.3
	P value	.04	.11	.99	.08	.7
Head-up	Foot	1.4 \pm 0.1	1.2 \pm 0.1*	1.3 \pm 0.1*	2.8 \pm 0.4*	1.3 \pm 0.1
	Calf	1.3 \pm 0.1	2.2 \pm 0.2	1.6 \pm 0.1	6.2 \pm 0.7	2.0 \pm 0.2
	Calf + thigh	1.7 \pm 0.2	2.8 \pm 0.2	1.8 \pm 0.1	5.1 \pm 1.0	2.0 \pm 0.5
	P value	.09	<.0001	.02	.002	.3
Difference between positions	P value (foot)	.04	.03	.4	.8	.02
	P value (calf)	.2	.2	.9	.3	.0003
	P value (calf + thigh)	.99	.02	.1	.2	.7

Increase is defined as ratio of volume flow during IPC over its baseline value in each extremity in each position. Mean values (n = 12) are listed for each compression garment used in each position of body. P values listed for one-way analysis of variance comparison of three garments.

*Values significantly different from those for other garments (Tukey post hoc test). Difference between positions was determined with two-way analysis of variance separately for each venous segment.

Table V. Comparison of MPV in venous segments during leg elevation and during IPC

Venous segment	Elevation of legs MPV (cm/s)	IPC in position:					
		Head-down		Horizontal		Head-up	
		MPV (cm/s)	P value	MPV (cm/s)	P value	MPV (cm/s)	P value
CFV	30.4 \pm 2.2	38.3 \pm 2.4	<.001	42.1 \pm 3.2	.002	39.5 \pm 2.6	.001
SFV	31.1 \pm 2.7	53.7 \pm 5.7	<.001	54.7 \pm 7.1	<.001	55.0 \pm 4.31	<.001
PFV	21.6 \pm 1.5	29.5 \pm 2.1	<.001	30.3 \pm 2.6	.011	27.0 \pm 3.4	.16
Popliteal vein	7.4 \pm 1.1	33.7 \pm 4.4	<.001	43.0 \pm 6.6	<.001	42.6 \pm 5.5	<.001
GSV	19.3 \pm 1.3	27.1 \pm 1.8	<.001	23.4 \pm 2.7	.115	27.1 \pm 2.2	.002

P values listed for paired *t* test comparison of MPV values during IPC with MPV values in head-down position without compression.

Table VI. Comparison of volume flow in deep veins of thigh, popliteal vein, and GSV during leg elevation and during IPC

Venous segment	Elevation of legs Flow (mL/s)	IPC in position:					
		Head-down		Horizontal		Head-up	
		Flow (mL/s)	P value	Flow (mL/s)	P value	Flow (mL/s)	P value
SFV + PFV	16.3 \pm 0.8	18.4 \pm 0.6	.002	22.6 \pm 1.5	<.001	23.7 \pm 1.2	<.001
Popliteal vein	3.5 \pm 0.5	14.8 \pm 1.7	<.001	18.5 \pm 2.1	<.001	19.3 \pm 2.8	<.001
GSV	3.8 \pm 0.3	5.3 \pm 0.4	.001	4.1 \pm 0.4	.4	4.8 \pm 0.4	.012

P values listed for paired *t* test comparison of MPV values during IPC with MPV values in head-down position without compression.

of one highly accelerated wave (flush) during compression cycle. In the absence of this important information, we decided to study all of these hemodynamic parameters, namely the volume flow, the maximum peak velocities, and the increase of velocities during pneumatic compression.

The use of ultrasound scan technology as an investigational tool introduces certain limitations. Unlike velocity measurement, which has become a part of everyday clinical practice despite its limitations and inaccuracy, volume flow

estimation is not a widely practiced procedure. As an exception, volume flow has been used in two prominent studies particularly to assess the effect of IPC on venous hemodynamics.^{3,4} The volume flow values are known to vary between individuals and within the same individual over time. Use of standard settings can significantly decrease this variability and make this measurement repeatable within the same individual.⁸ Although ultrasound scan measurements overestimate true volume flow, the systematic error

is constant.¹¹ On the basis of these findings, relative values or ratios were used in this study, instead of absolute values of the volume flow. Volume flow increase was used as an outcome measure and was defined as a ratio of volume flow during IPC over the baseline value. The same compressor with the same cycle was used for all experiments in this study. The inflation time was the same for all garments. Therefore, the increase of velocities (ratio of MPV during IPC over baseline value) was used as the measure of flow acceleration.

The three hemodynamic outcome measures (MPV, velocity increase, and volume flow increase) provide different information on changes in venous hemodynamics. MPV values show the actual velocities that can be achieved during compression. They depend on the baseline values, which are different in different positions of the body (Table II). Velocity increase provides information on magnitude of the compression's effect. It allows comparison of different body positions and compression garments because it does not depend on baseline values (Table III).

There are important limitations in use of velocities for estimation of IPC effect on hemodynamics. First of all, increase of velocities is often associated with rapid decrease in venous diameter and can be observed with the constant volume flow through the segment.⁷ Second, the high velocity wave caused by compression is always followed by a long no-flow pause and then by a number of low velocity waves. Mean volume flow during the whole compression-decompression cycle provides information on integrated influence of IPC on the segmental hemodynamics that cannot be derived from the velocity measurements alone.

The first part of this study established the flow volumes and velocities in the three positions of horizontal, 15-degree head-down, and 15-degree head-up, without a pump in place. This showed an increase of flow limited to the SFV and the CFV segments when legs were elevated and a decrease of flow limited to the CFV, the SFV, and the PFV segments when the head was elevated, when compared with flow in the horizontal position. The conclusion is that these modest but significant flow changes with different positions reflect changes in the thigh flow but not in the popliteal flow.

The second part of the study addressed segmental flow and velocities changes in various positions when the pump was used on the foot, on the calf, and on the calf and the thigh simultaneously (calf + thigh). The findings in these studies were multiple. It was seen that the flow and velocity increase significantly with the use of the pump, and these increases were either the same or even greater when the subject was placed in the head-up position. In addition, flow and velocity increases were found in the popliteal vein, which certainly reflects increased flow in the calf veins where prophylaxis of DVT could be expected to be most effective. It may be concluded from these results that mechanical pumping stimulates increases of flow volume and velocity in the calf and in the deep thigh veins when the subject is in the horizontal, head-up, or head-down positions and that IPC is superior to elevation of the extremities

for DVT prophylaxis (Tables V and VI). This lends credence to the use of mechanical pumping when the patient is at bed rest in the head-up or the horizontal position. The foot pump was effective in increasing flow and velocity in the calf and popliteal veins, which suggests the value of its use in surgery of the knee, especially in total knee replacement where the incidence rate of calf vein thrombi is known to be so high.

For maximal increase of flow and velocity, the calf compression is most effective in the SFV flows and velocities and to a lesser extent in the PFV and the GSV dynamics. This effect in deep veins is not materially changed with addition of a thigh cuff. These findings support the use of calf compression in hip patients where increases of flow and velocity of both the calf and the thigh veins are desired. These flow increases appear important in any patient on bed rest, particularly in the patient who is in the head-up position, such as the pulmonary or cardiac patient.

Among the questions not addressed in this study is whether the effect of IPC changes over time, while the circulatory system of extremity adjusts to new conditions. Segmental outflow, especially in collectors such as the CFV and the popliteal veins, is intimately related to arterial inflow. If the leg stays the same size, increased flow may occur transiently with compression, but during deflation, flow should diminish with regard to baseline, resulting in an unchanged overall mean flow. We did not measure the volume of the leg; therefore, its changes are unknown. However, it is consistently observed that the leg's volume can notably decrease with combination of external compression (elastic stockings) and walking. Perhaps, IPC can cause the same change. It has been also shown (with a different IPC device) that pneumatic compression can cause significant increase of arterial inflow into extremity.¹² Our hemodynamic measurements were limited to the first three cycles of IPC. It is possible, that with time, the effect of compression can change.

In summary, IPC produces significant increases of venous flow volume and flow velocity and acceleration of flow, when compared with baseline flow without a pump. This is true whether the limbs are elevated, horizontal, or dependent. Segmental flow changes vary with the position of the patient and the placement of the compression garment on the extremity. Foot compression provides meaningful increases of volume flow and flow velocity primarily in the calf and popliteal veins. Calf compression provides maximal increases of volume flow and flow velocity through the deep veins of the calf and thigh. This effect in deep veins is not materially changed with addition of a thigh cuff. The physiologic effects reported in this study provide support for the use of IPC and provide guidance for the choice of position and location of the compression garment on the extremity for different clinical applications.

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