Applications of Intermittent Pneumatic Compression for Diagnostic and Therapeutic Purposes

Applications of Intermittent Pneumatic Compression for diagnostic and therapeutic purposes

Carlo Ferraresi[1], Walter Franco[1], Daniela Maffiodo[1], Carlo De Benedictis[1*], Maria Paterna[1], Daniel Pacheco Quiñones[1], Leonardo Ermini[2], Silvestro Roatta[2]

[1] Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Turin (Italy)
[2] Laboratory of Integrative Physiology, Department of Neuroscience, University of Torino, Turin (Italy)
carlo.debenedictis@polito.it

Abstract. Intermittent Pneumatic Compression (IPC) technique is prescribed for several treatments, as the management of venous leg ulcers or the prevention of deep vein thrombosis. Commercial devices do not enable the full customization of the compressive patterns due to design specifications and low dynamics. However, IPC can be implemented in a wide scenario of clinical protocols, and not only as a therapeutic tool. In this paper, the results of the research on IPC devices conducted at the Politecnico di Torino (Turin, Italy) are presented. In particular, applications regarding the treatment of the end-diastolic volume (EDV) reduction, the investigation of vascular phenomena as hyperemia, and the assessment of venous pulse wave velocity (vPWV) are discussed. The outcomes of the research demonstrate that IPC technology can lead to the creation of widely used diagnostic, therapeutic and rehabilitative devices.

Keywords: SDG3, therapeutic and rehabilitative devices, intermittent pneumatic compression, hemodynamics, hyperemia, vPWV, pneumotronics, human-machine interaction.

1 Introduction

In an extensive sense, Intermittent Pneumatic Compression (IPC) represents the application of mechanical pressure stimuli on a person's body, which can be either periodic or impulsive. An IPC device consists of one or more inflatable sleeves and an inflating system that allows a controlled and well-defined pressure trend to be applied to the lower or upper limbs of patients. In a first possible application, the applied compression may mimic the action of the muscle pump and promote venous return. For this reason, it can be used for the treatment of various pathologies, such as lymphedemas [1, 2], venous leg ulcers [3, 4, 5], prevention of deep vein thrombosis [6, 7], and for the treatment of subjects with limited mobility due to recent surgery or pathological condition.

IPC devices come with either single or multi-chamber sleeves [5]. The latter can provide sequential compression that can push the blood to the central part of the patient’s body; the single-chamber devices, instead, produce controlled compression that is focused to a defined point of the body. The choice of one or the other type of device depends only on the specific application. In recent years, in order to improve the venous blood return and to prevent a reduction in left ventricle end-diastolic volume (EDV) in subjects with a walking disability, a multi-chamber IPC device has been developed at Politecnico di Torino [8, 9, 10].

In another application, Ferraresi et al. [11] describe a single chamber IPC device with high dynamic performances and capable to apply a customizable pressure pattern to the limbs of the subject. The device is therefore particularly suitable for research purposes oriented to better understand the mechanism behind the hyperemic response that develops in response to compression stimuli and its attenuation following consecutive compressions [12, 13]. The same device was also employed in a different application, oriented to the non-invasive assessment of a subject's volemic status [14, 15]. It is based on the generation and measurement of the propagation velocity of a pressure wave in the veins, namely the venous Pulse Wave Velocity (vPWV), which is related to vessel stiffness and therefore to vascular filling. The PWV has been used for years to monitor the stiffness of the arteries [16, 17, 18], but it is difficult to use it to monitor the venous compartment due to the lack of natural pulsations that therefore must be generated by the IPC device.

This work presents the outcomes of the research activity on IPC devices carried out by the group of functional biomechanics at the Department of Mechanical and Aerospace Engineering (DIMEAS) of Politecnico di Torino, Italy. The activity detailed in this work was carried out in collaboration with relevant research centers, in particular the Laboratory of Integrative Physiology of the University of Torino, Italy and the Laboratory of Sports Physiology of the University of Cagliari, Italy. The diversity of the applications shown in this paper and in the literature signals the relevancy of the research theme. In fact, the improvement of treatments for cardiovascular diseases and the definition of new methodologies for the investigation of hemodynamics are well in agreement with the rationale behind SDG3 promoted by the United Nations, which aims at ensuring healthy lives and well-being.

2 IPC device for the improvement of venous blood return

Patients with a walking disability are subjected to a reduction in the EDV of the left ventricle, since the blood pressure gradient between the right atrium and the postcaval vein is normally supplied by effects related to locomotion, as the rhythmic contraction of the triceps surae which compresses the veins in the calf. For this reason, a device aiming to generate intermittent stimulation to the lower limbs can be effectively used to improve the cardiac functionality in those patients.

Ferraresi et al. [8], on the basis of a mathematical modeling, created a multi-bladder IPC device designed to favor the return of venous blood in people with motor deficit in the lower limbs. The mechatronic system was provided with six inflatable bladders integrated within two shells, each mounted on a separate segment (calf and foot, see Fig. 1). The bladders were designed to direct the pneumatic energy towards the limb without dispersion related to the deformation of the materials. Thanks to compliant and air-tight material, as well as to proper shaping of each bladder, it was possible to achieve good performance of the IPC device.

The control system was based on a group of six 3-way electro-pneumatic valves, six pressure sensors and a programmable logic controller. The valves and pressure sensors were mounted on the calf shell, in order to improve the dynamic performance of the pneumatic system.

Subsequently, Manuello Bertetto et al. [9] applied this device in experimental trials, for objective evaluation of its effectiveness in the enhancement of venous blood return. To assess EDV non-invasively, an equipment able to measure the thoracic electrical bioimpedance was used.

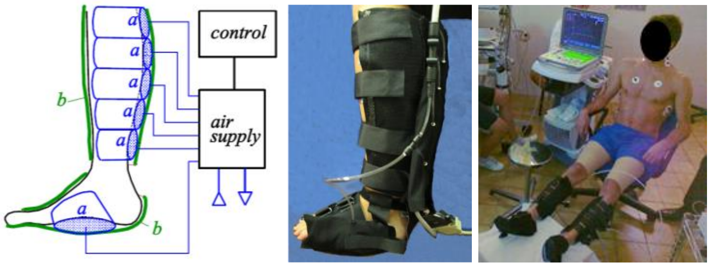

Fig. 1. Pneumotronic IPC device for the improvement of venous blood return; application in experimental trials for EDV assessment.

Compression-relaxation protocols were designed considering the alternating activation of two sleeves to simulate the muscle pattern during locomotion. The mechatronic device was tested on 19 healthy voluntary participants, which were initially monitored for 3 min to collect TEB baseline values. During the experimentation, which involved activation-deactivation sequences following a peristaltic compression (caudal-rostral trend), the EDV increased of about 10% with respect to preliminary observation done during initial monitoring of the subjects.

Although the study did not consider patients unable to walk or bed-ridden, it confirmed the relevance of the implementation of such IPC devices for the treatment of conditions related to reduction of venous blood return.

3 IPC device for the study of vascular phenomena

Besides therapeutic treatments, IPC devices can be effectively used to examine in-depth vascular phenomena as hyperemia. Ferraresi et al. [11] presented the design and modeling of an IPC device aimed at providing customizable pressure profiles to human limbs, whereas Messere et al. [12, 13] showed applications of such device on a set of healthy subjects, aimed at developing protocols for the study of the mechanisms behind hyperemia (i.e., the local increase of blood flow to tissues).

The device, shown in Fig. 2, was based on a pneumatic circuit used to inflate a blood pressure cuff wrapped around the limb to stimulate. In order to achieve appropriate responses, it was designed to control the pressure with a step reference of magnitude between 0 and 250 mmHg, with critical attention given to static and dynamic performance.

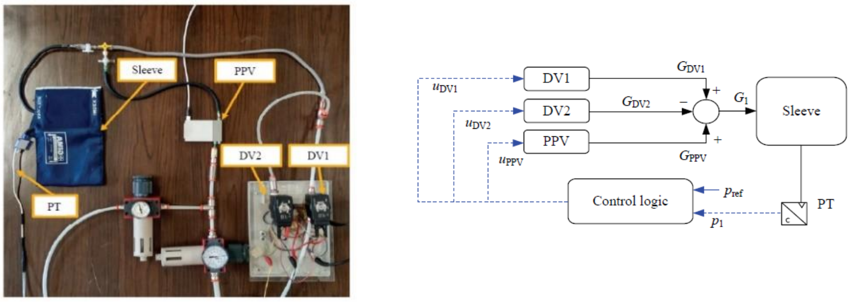

Fig. 2. Picture (left) and scheme (right) of the pneumotronic system [11]. DV1 and DV2 are the digital valves respectively used to charge and discharge the cuff, PPV is the pressure proportional valve, PT is the pressure transducer.

In order to fulfil the required specifications of accuracy and short time response, a pneumatic circuit based on the combination of 2/2 digital solenoid valves and a pressure proportional valve, shown in Fig. 2, was designed. The digital valves (DV1 and DV2) were used to quickly charge and discharge the cuff, while the compact pressure proportional valve (PPV) was used to accurately control the level of pressure inside the cuff. A control system, combined with a pressure transducer PT positioned inside the cuff, was used in the final architecture to drive the valves, depending on the operating conditions of the system.

In order to investigate the sensitivity of the device to the variation of some physical parameters, an analytical model was implemented. In particular, the interaction between the cuff and the biological tissues was studied to achieve an accurate matching between the model and experimental data.

The final design of the pneumotronic IPC device showed high dynamic performance and was able to provide sharp, customizable stimuli to the limb of a subject (see Fig. 3) in a wide range of pressure, necessary for the investigation of several vascular phenomena with different dynamics.

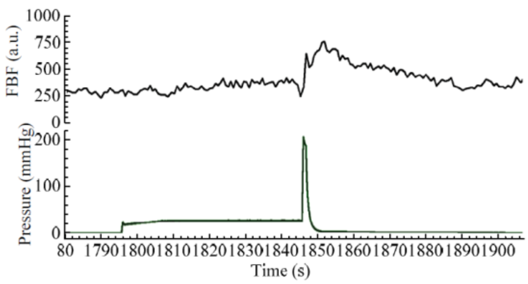

Fig. 3. Recordings of a post-compression hyperemia from a representative subject: femoral artery blood flow (FBF) and cuff pressure [11].

3.1 Investigation of vascular reactivity to mechanical stimuli

Resistance vessels in skeletal muscle exhibit a rapid dilatation in response to mechanical stimuli, such as short-lasting external compressions, whose underlying mechanisms are still unclear. Messere et al. [12] performed an analysis on 10 healthy volunteers with the IPC device described in the previous section. The subjects sat on a chair with a backrest, the leg fully extended with the cuff wrapped distally to the knee. The protocol started after 10 min of rest and provided customized pressure patterns. With respect to traditional devices, that are often meant to apply fast and short-lasting stimuli, the custom-design IPC device was necessary to generate sequences of static pressure levels that can be considered to modulate vascular filling in venous compartments as well as pressure gradients across the wall of the vessels.

During the compressions, the blood flow of the femoral artery (FBF) was measured by Eco-Doppler sonography. The flow response highlighted a significant increase of FBF after the occurrence of the high-level compression. Preliminary investigations showed suitable performance of the device for the investigation of vascular phenomena behind the compression-induced rapid hyperemia that still do not have a univocal interpretation [19 – 24].

Another relevant issue recently investigated is the role of tissue oxygenation in shaping the magnitude of this mechanically-induced rapid hyperemia. Messere et al. [13] hypothesized that increased tissue oxygenation could explain the progressive attenuation of the hyperemia in response to repetitive stimulation. To measure local hemodynamic changes, a continuous wave near-infrared spectroscopy (NIRS) device was used, providing a tissue oxygenation index. The NIRS measurement was obtained for wrist extensor muscles and for the lateral head of the gastrocnemius muscle of the right leg, since two different stimulation points were considered (Fig. 4).

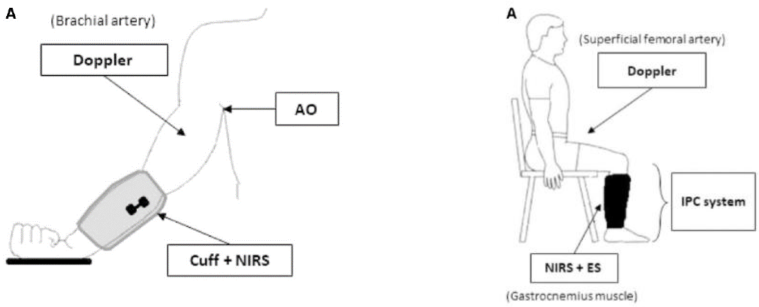

Fig. 4. Set-up of the 1st (left) and 2nd (right) protocol for the investigation of hyperemia [13].

In the first protocol, the IPC device was used to deliver two series of two compressive stimuli to the forearm with a time interval of 25 s between each compression, with peak pressure 250 mmHg and duration 1 s (Fig. 4, left). In the first series, the hyperemia was not limited, whereas it was prevented after the first compression in the second series. It was observed that preventing the hyperemia and the ensuing increases in oxygenation also prevented the attenuation of the hyperemic response to a subsequent stimulus.

The second protocol was designed to understand if the tissue oxygenation produced by a compression or a muscle contraction (which similarly compresses intramuscular vessels) affects the hyperemia generated by a subsequent compression or contraction of the same muscle (Fig. 4, right). During this protocol, the lateral gastrocnemius of the right leg was stimulated by means of an electrical stimulator at 20 Hz frequency. Compression of the leg was obtained with an IPC system including four bladders, with peak pressure 150 mmHg and duration of about 2-3 s. Several combinations of muscle contraction and pneumatic compression were considered.

The results of the study demonstrated that the hemodynamic responses to muscle contraction and to limb compression are very similar, suggesting a common underlying mechanism related to mechanical deformation of blood vessels. Moreover, the results showed, for the first time in humans, that the tissue hyper-oxygenation has a significant role in limiting further responses in skeletal muscle.

4 IPC in the study of venous compartment hemodynamics

As discussed in Section 3, IPC technique can be employed to investigate vascular phenomena and not only as a therapeutic tool in patients with some deficits as EDV reduction (Section 2). Moreover, IPC devices can also be used to generate pressure pulses in veins to allow for the measurement of Pulse Wave Velocity (vPWV).

4.1 IPC as a tool in a system for the measurement of venous PWV

Ermini et al. [14] carried out a study on 8 healthy volunteers with a revised version of the IPC device shown in Section 3. The experimental set-up is shown in Fig. 5. A compressive stimulus was delivered directly to the foot by inflating a pneumatic cuff. The peak pressure considered was equal to 200 mmHg, with a duration of 1 s and inflation time of 400 ms. The foot compression was used to create a pressure pulse that propagated along the veins until it was detected by a Doppler ultrasound system at superficial femoral vein (SFV) level. The venous blood velocity was recorded with a linear probe positioned on the leg, with an incident angle of about 60°.

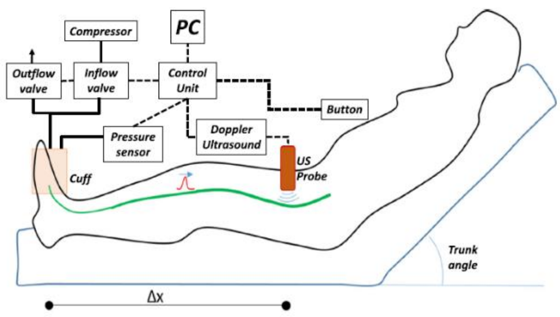

Fig. 5. Set-up for the measurement of vPWV in response of different trunk orientation [14].

A pressure transducer was positioned on the cuff outlet and used to monitor the pressure inside the inflating volume (Fig. 6a, bottom), whereas leg venous pressure (LVP) was estimated as the hydrostatic load relative to the vertical distance between the leg and the venous point of collapse, which was detected by a second dedicated ultrasound system. The Doppler signal was sampled at 10 kHz (Fig. 6a, top) and used to extract the maximum velocity profile (Fig. 6c). The footprint of the latter, detected by a custom-made algorithm, was used to calculate the transit time of the pulse wave. The vPWV was then calculated as the ratio between the traveled distance (measured between the ankle and the probe positions) and transit time.

The trigger of the stimulation was provided directly by the participant subject with a button, at the end of the expiratory phase in order to reduce the interference between the vPWV assessment and the respiratory activity and to improve the reproducibility of the measurements.

This study provided a significant proof of concept for a new methodology focused on the calculation of vPWV. Although PWV can be reliably assessed in arteries, where it is a well-established marker of cardiovascular risk, the measurement of vPWV has not been investigated with the same attention. In particular, the lack of relevant pulsation in the venous compartment, as well as the low blood pressure levels involved, represent significant limitations for a reliable measurement. For these reasons, the use of an IPC device can be really effective in generating the pressure pulse required for such measurement. The results of the study, in terms of vPWV values, were compatible with those obtained with different techniques (1-3 m/s for supine position, 4-15 m/s in the arm for venous pressures of 20-80 mmHg). Moreover, the linear relationship observed between vPWV and LVP was compatible with the literature [25 – 28] and confirmed that vPWV assessment could represent an indirect estimation of the venous pressure, which is directly connected to the volemic status of a patient.

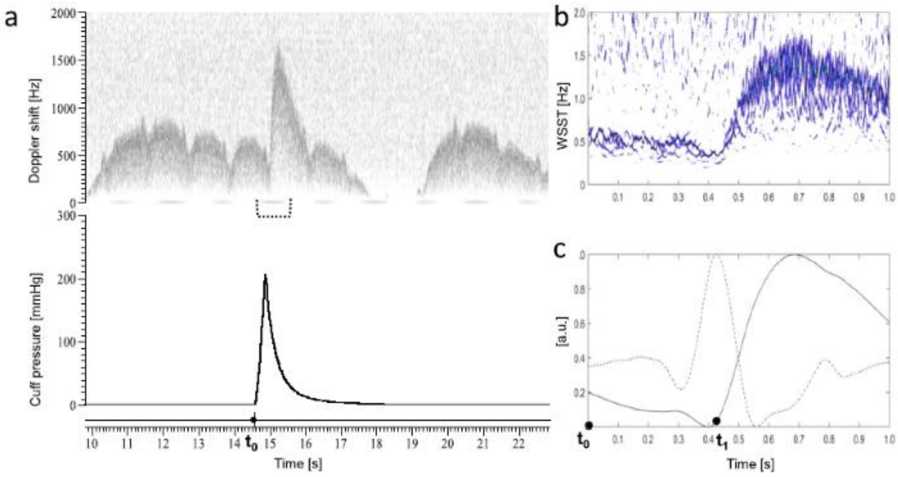

Fig. 6. Representative acquired and processed signals. (a) Venous pulse wave detected by Doppler ultrasound (top) and compressive stimulus profile (bottom). (b) Wavelet synchro-

squeezed transform (WSST) of the Doppler signal. (c) Smoothed normalized maximum energy profile of WSST (solid line) and its normalized second derivative (dashed line), whose maximum identifies the footprint of the profile which was used to calculate the transit time of the pulse wave [14].

4.2 Estimation of vPWV in response to a simulated fluid change

Ermini et al. [15] conducted an experiment on 15 healthy volunteers with a modified version of the IPC device shown in the previous section. In particular, the system was used to measure the vPWV along the arm, through a synchronous delivery of the compression (at the hand) with respiratory and cardiac cycles. The hemodynamic perturbation was realized by means of passive leg raising (PLR) maneuvers. An overview of the experimental set-up is given in Fig. 7. A fast compression (peak pressure: 400 mmHg, lasting about 1 s, inflation time: 400 ms) was delivered to the hand of each subject through the cuff.

A Doppler ultrasound system was used to detect the pressure pulse propagating proximally at the level of the basilic vein (BV). To further improve the quality of the measurements, the detection was synchronized with both respiratory and cardiac activities. In particular, the measurement was always performed at the end of the expiratory phase and at the same time instant within the cardiac cycle, corresponding to the lowest blood velocity. Cardiac synchronization was assessed by monitoring of the R-wave with a commercial ECG system.

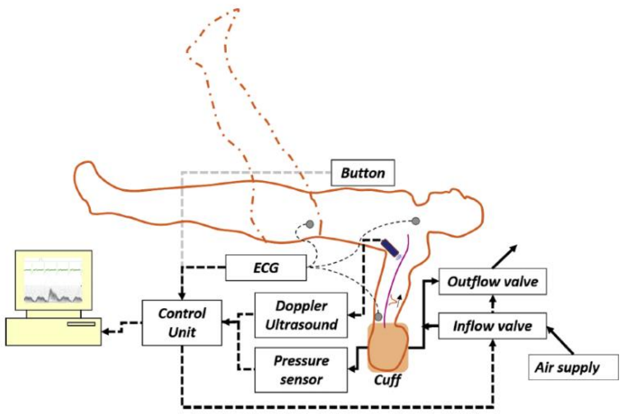

Fig. 7. Set-up to estimate vPWV in response of passive leg rising maneuvers [15].

This study showed for the first time that vPWV is sensitive to simulated changes in blood volume, as produced by PLR. With respect to traditional techniques, this methodology is objective. Furthermore, the measurement is sensitive even to limited hemodynamic challenges, and it is not invasive. Given the relationship between vPWV and the volemic status of a patient, this technique could be used for monitoring purposes or to provide a quantitative assessment of vascular filling during fluid administration in patients.

5 Conclusions

The applications of IPC technique can be of a therapeutic and rehabilitative type, such as the improvement of the return of venous blood to the heart in people with disorders to the cardiovascular system, or of a diagnostic type, such as the measure of the propagation velocity of a pressure wave in the venous compartment, which allows an indirect evaluation of the volemic status of a subject. Further applications can deepen the study of still poorly defined phenomena in the cardiovascular system.

The variety of applications from the physiological point of view requires that the specific IPC device must be designed and manufactured with non-common techniques, to meet the required precision and dynamic performance.

The applications of IPC are completely non-invasive, and this constitutes a fundamental element for the realization of devices of limited cost, easy to use and therefore very widespread. They can therefore represent an important means of spreading well-being and good health widely, in the spirit of the SDG3 of the United Nations Development Program.

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