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Determination of comprehensive arterial blood inflow in abdominal-pelvic organs: Impact of respiration and posture on organ perfusion

Authors' Contribution:

- A** Study Design
- B** Data Collection
- C** Statistical Analysis
- D** Data Interpretation
- E** Manuscript Preparation
- F** Literature Search
- G** Funds Collection

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Summary

Background:

Arterial blood flow (BF) to all abdominal-pelvic organs (AP) shows potential for an indicator of comprehensive splanchnic organ circulation (reservoir of blood supply for redistribution) in cardiovascular disease, hepato-gastrointestinal disease or hemodynamic disorders. Our previous assessment of splanchnic hemodynamics, as magnitude of BF_{AP} [measuring by subtracting BF in both femoral arteries (FAs) from the upper abdominal aorta (Ao) above the celiac trunk] using Doppler ultrasound, was reported as the relationship between Ao and FAs, day-to-day variability and response to exercise. For accurate determination of BF_{AP} , it is important to consider the various factors that potentially influence BF_{AP} . However, little information exists regarding the influence of respiration (interplay between inspiration and expiration) and posture on BF_{AP} .

Material/Methods:

Ten healthy males were evaluated in sitting/supine positions following a 12 hr fast. Magnitude of BF_{AP} was determined as measurement of Ao and FAs hemodynamics (blood velocity and vessel diameter) using pulsed Doppler with spectral analysis during spontaneous 4-sec inspiration/4-sec expiration phases.

Results:

BF/blood velocity in the Ao and FAs showed significant lower in inspiration than expiration. BF_{AP} showed a significant ($P<0.005$) reduction of ~20% in inspiratory phase (sitting, 2213 ± 222 ml/min; supine, 2059 ± 215 ml/min) compared with expiratory phase (sitting, 2765 ± 303 ml/min; supine, 2539 ± 253 ml/min), with no difference between sitting and supine.

Conclusions:

Respiratory-related to alterations in BF_{AP} were observed. It may be speculated that changes in intra-abdominal pressure during breathing (thoracic-abdominal movement) is possibly reflecting transient changes in blood velocity in the Ao and FAs. Respiratory effects should be taken into account for evaluation of BF_{AP} .

key words:

splanchnic blood flow • conduit artery • respiration • postural change • Doppler ultrasound

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BACKGROUND

Clinical examination of the hemodynamics of the feeding arteries that supply blood flow (BF) to the splanchnic organs can indicate the diagnosis and severity of ischemic gastrointestinal disease such as a ischemic colitis [1,2], as well as hepato-splenic disease [3] and portal hypertension [4].

However, previous reports that measured BF using ultrasonography in a "single vessel with small size volume", such as the superior mesenteric and celiac arteries, were concerned solely with the target organ in the gastrointestinal area [5,6] under various patho-physiological conditions or stressful overload; therefore, evaluation of alterations in these single arterial BFs under various states were sometimes limited to "small blood volumes" [7], even though there was a relatively large change in flow.

Provided that measurement could be conducted to encompass physiological function in the multiple abdominal organ systems, evaluation of the comprehensive arterial BF of all of the abdominal-pelvic organs (AP) (liver, spleen, gastro-intestine, kidney, and pelvic organs) as a multiple arterial function may be a feasible clinical method for determining the BF distribution of AP in cases of splanchnic or cardiovascular dysfunction with accompanying hemodynamic disorder. This measurement also potentially provides an indicator of digestive absorption or food intake related to splanchnic hemodynamics, and may potentially provide additional information regarding the reserve of blood in the splanchnic area that contributes to cardiovascular adjustment e.g., severe septic shock [8], orthostatic hypotension [9], and hemorrhage [10]. In addition, evaluation of basal volume capacity, with the reserve function of supplying blood to other tissues [11] as comprehensive splanchnic organ circulation, provides valuable information that can be used in the investigation of various clinical crises.

To develop the use of the above-mentioned measurement, our initial work used ultrasonography to assess whole arterial hemodynamics BF_{AP} ; we calculated BF_{AP} by subtracting BF in the bilateral proximal femoral arteries (FA) from BF in the upper abdominal aorta (Ao) above the celiac artery bifurcation [12–14] (Figure 1). This method of quantitative assessment is a challenging, but unique and valid procedure for determining the encompassing/comprehensive physiological BF_{AP} . However, the measurement phase for determining BF_{AP} above mentioned procedure was performed in the three conduit arteries only during the "end of expiratory phase" through spontaneous shallow breathing, with the subjects in the "sitting position" to maintain fixation of the probe while measuring Ao and to avoid interference caused by imperceptible thoracic distension and abdominal movement during the inspiratory phase.

For accurate determination of BF_{AP} , it is important to consider the various factors that potentially influence BF_{AP} . In this regard, there is a lack of information regarding the respiratory cycle as well as postural change. The hypothesis of the present study is that important interplays exist between respiration and Ao/FAs that must be taken into account when evaluating BF_{AP} . Therefore, the aim of the present study was to determine the influence on BF_{AP} of respiratory-related alterations and effects of posture in hemodynamics in the Ao and FAs.

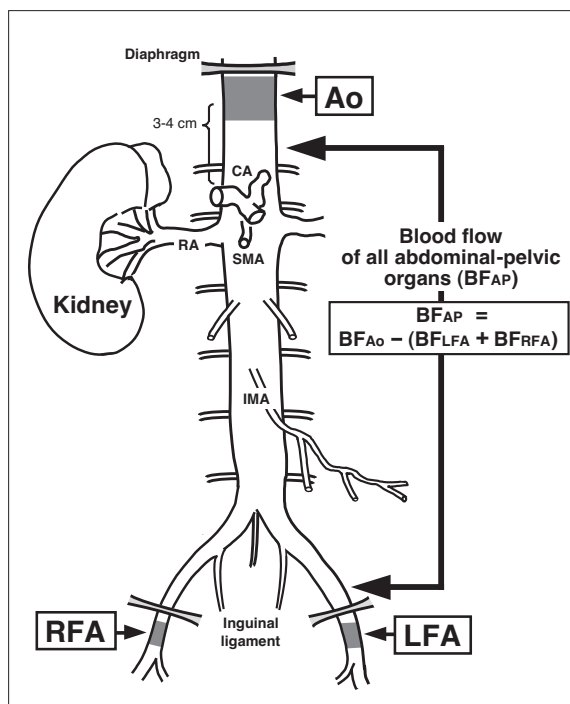


Figure 1. Schematic anatomic illustration of the three measured conduit arterial vessels. Blood flow (BF) measurements were obtained for the Ao above the celiac artery bifurcation and for the bilateral LFA and RFA. BF to the abdominal-pelvic organs (BF_{AP}) was calculated by subtracting bilateral femoral arterial flow ($BF_{LFA} + BF_{RFA}$) from BF_{Ao} . BF_{AP} is a comprehensive measurement of total BF supply to the splanchnic gastrointestinal blood vessels, primarily the celiac (CA) and superior (SMA) and inferior (IMA) mesenteric arteries, as well as the renal arteries (RA), internal iliac arteries, and other minor arteries that supply the pelvic organs. Other abbreviations see in Table 1.

MATERIAL AND METHODS

Subjects

Ten male volunteers participated in the experiments (mean age \pm SE, 25.2 ± 2.1 years; range, 20–39 years; mean height, 175.6 ± 2.2 cm; range, 165.1–184.6 cm; mean body weight, 70.1 ± 2.4 kg; range, 60.2–82.3 kg). Subjects had no previous history of cardiovascular disease, gastrointestinal disease, hypertension, or anemia, and no abnormality of the peripheral vasculature. The study was conducted according to the principles of the Declaration of Helsinki (1976) and with the approval of the Institutional Ethics Committee of the authors' institution. All participants gave their written consent and were informed of the nature and purpose of the study, as well as potential risks and discomfort. The participants also understood that they could withdraw from the study at any time without consequence.

Doppler instrumentation

Hemodynamic parameters were determined using a Doppler unit (SONOS 1500, HP77035A; Hewlett-Packard, Tokyo, Japan) with a real-time two-dimensional ultrasonic imager,

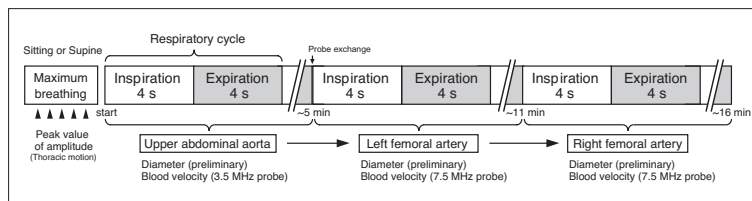


Figure 2. Experimental protocol.

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a pulsed-Doppler flowmeter, and a videotape recorder (AG-7350-P; Panasonic, Tokyo, Japan).

Blood velocity and vessel diameter measurements were performed using pulsed Doppler and two-dimensional images with a curvilinear array probe operating at 3.5 MHz (Ao), and with a linear array probe operating at 7.5 MHz (FAs). In the present study, the insonation angle was maintained at 60° for each subject and remained constant throughout the experiments [15]. The anterior and posterior edges of the sample volume were positioned to overlie the inner anterior and inner posterior vessel walls, respectively. Both edges of the sample volume were widely bounded by the intima-media complex layer to reduce noise in the blood velocity profile arising from up-down movement of the Ao during breathing and FAs. Vessel diameter was measured under perpendicular insonation and defined in relation to the temporal duration of the electrocardiogram recording curve, corresponding with the end-diastolic phase. Prior to measurement, color Doppler was used to detect unsuspected pathology in each conduit vessel.

Location of measured three conduit arteries and determination of BF_{AP}

The target measured vessels were in the following three conduit arteries: 1) the Ao 3–4 cm above the celiac artery bifurcation, 2) the proximal left common femoral artery (LFA), and 3) the proximal right common femoral artery (RFA), below the inguinal ligaments, 1 cm above the bifurcation to the superficial and deep femoral arteries in Figure 1.

In hemodynamic measurements of Ao, positioning of the detection probe in the substernal area achieved relatively stable recordings, although respiratory-induced upper body/truncus motion (thoracic as well as abdominal movement) was observed during measurement. Detection of the Ao was relatively constant and free from interference from intestinal gas throughout the cardiac cycle [7,12–14].

We noted that for the deep Ao region (generally located just below the diaphragm), the best choice of position was a relatively deep location at 3–4 cm above the celiac artery bifurcation in longitudinal section view, because it enabled Ao sample volume to be maintained while the Ao moved up and down during the respiratory cycle.

In the present study, detection of each FA was also found to be relatively constant during the respiratory cycle between sitting and supine. For the FAs, measurement location was chosen to minimize turbulence from 1 cm above the bifurcation and from the influence of the inguinal region on BF, thereby enabling easy and reliable measurement of blood velocity spectra [16–19]. The process of blood velocity measurement with the insonation angle in FA was similar

between sitting and supine. The monitoring for FA during sitting position was less influenced by the hip joint bent.

Measurements were first obtained for the Ao, followed by the LFA and RFA (Ao→LFA→RFA) (Figure 2). BF_{AP} was calculated by subtracting the sum of BF_{RFA} and BF_{LFA} from BF_{Ao} , according to the following equation: $BF_{AP} = [BF_{Ao} - (BF_{LFA} + BF_{RFA})]$ [12–14] (Figure 1). Based on the general anatomical features, estimated BF_{AP} was defined as the comprehensive BF in the splanchnic-gastrointestinal organs via the celiac artery and both mesenteric arteries, in the kidney via both renal arteries, in the pelvic organs via the iliac arteries, as well as BF in various minor arteries to musculature and other structures.

Respiratory protocol and posture

To minimize the influence of intra-abdominal pressure during the experiment, subjects were asked to perform normal/natural spontaneous breathing without intentional abdominal movement. In addition, the subjects were requested not to expand the chest wall excessively or perform abdominal breathing intentionally. Normal respiration was considered to be 4 s of active inspiration followed by 4 s of passive expiration. Therefore, we defined normal respiration as normal, quiet, natural, unconscious/spontaneous breathing (inspiration and expiration alternating every 4 s; duration of breath, 4 s; respiration frequency, 7.5 breaths/min).

This above-mentioned rhythmical spontaneous inspiratory-expiratory cycle was continued for at least 5 minutes for each three-conduit arterial hemodynamic measurement (total duration of ~16 min, including 1 min to exchange the probe) (Figure 2). All subjects were familiarized with these respiratory features prior to beginning the experiment, and were made aware of the symptoms of hyperventilation during spontaneous breathing.

Respiratory amplitude was detected via thoracic movement (the amplitude of thoracic expansion) using a respiratory belt (Pneumotrace® II, MLT1132 Respiratory Belt Transducer, ADInstruments, Sydney, Australia) during respiratory cycle. The subjects maintained respiratory rhythm and amplitude, and used an audible metronome for pacing. The respiratory curve was displayed in real time on a monitor and recorded on a computer using the PowerLab® data acquisition system (Chart v. 4.2.3 software; ADInstruments, Sydney, Australia). We measured maximum thoracic movement (expansion) due to maximum breathing in each subject prior to initiating recording of spontaneous respiration.

Peak relative respiratory amplitude was calculated as “[peak amplitude in spontaneous respiratory cycle]/[peak amplitude in maximum breathing] × 100%” for evaluation of the variables of individual duty respiratory cycle and comparison

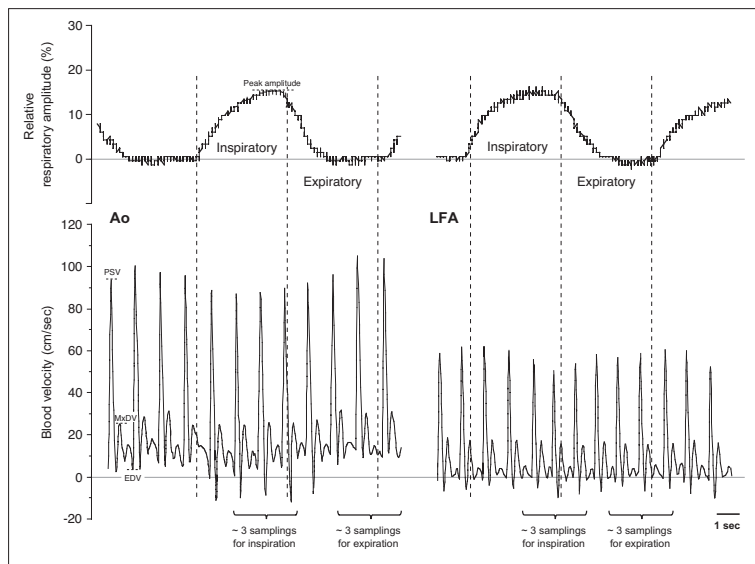


Figure 3. Alterations in blood velocity profile during respiratory cycle in a sitting position for one subject. The blood velocity profile differed between the inspiratory and expiratory phases in Ao and LFA. In particular, the magnitude of peak systolic velocity (PSV) and the blood velocity profile during diastole were lower during the inspiratory phase compared with the expiratory phase. Change in the blood velocity profile was stable at around 2–4 sec of the inspiratory phase and at approximately 1 sec immediately after the end of inspiration. Similarly, change in the blood velocity profile was stable at around 2–4 sec of the expiratory phase and at approximately 1 sec immediately after the end of expiration. Blood velocity was generally measured during this 3-sec period. Relative respiratory amplitude, determined using a respiratory band, may not be a direct indicator of changes in intra-thoracic pressure following respiration. Thus, the time point at which alteration in blood velocity profile begins may be identical to the beginning of the inspiratory or expiratory phase. MxDV, maximum diastolic velocity; EDV, end-diastolic velocity. Other abbreviations see in Table 1.

between the sitting and supine positions. The peak respiratory point generally corresponded to the end of the inspiratory phase (the end of thoracic expansion). Duration of respiration was defined as the time interval for completion of both the inspiratory and expiratory phases.

During the experiment, the subject sat on a chair with the leg extended and the knee at 110° of flexion. In the supine position, the subject reclined on a chair, with the leg extended and the knee at 110° of flexion. While the subject was positioned in the sitting or supine position, neither foot was allowed to touch the ground, to avoid the potential milking effects of slight muscle contractions.

Measurement of hemodynamics, and calculation of BF in the three-conduit arteries

Our previous data showed that the vessel diameter in these three target arteries remains constant during the transition from pre-exercising rest to even limb exercise [12]. In addition, because the three target vessels were conduit arterial vessels rather than resistance vessels, the change in vessel diameter would also remain constant during respiration. In preliminary testing, mean vessel diameter was calculated in relation to inspiration and expiration over approximately 20 beats, in both the sitting and supine positions. Preliminary testing showed no significant difference in determined vessel diameter between the inspiratory and expiratory phases. The vessel diameter values were similar between sitting and supine. Therefore, the vessel diameter values in the sitting position obtained in the preliminary test were used to calculate BF in the three conduit arteries in both the sitting and supine positions.

Following a 12-hour fast, the subject performed maximum breathing 5 times to determine the relative motion of thoracic movement following relaxation for 10 min. Blood velocity measurements were conducted simultaneously during the duty respiratory cycle for approximately 5 min in each of the three arteries. Approximately 1 min was allowed for exchanging the probe 3.5 MHz probe to the 7.5 MHz probe. Both the sitting and supine experimental protocols

were performed on the same day. We verified that a sufficient amount of time had elapsed between the sitting and supine trials for blood velocity to return to the resting control levels.

For each subject, measurements were made over 25–30 respiratory cycles to determine the average blood velocity in the three conduit arteries at the expiratory and inspiratory phases. Peak systolic velocity (PSV), maximum diastolic velocity (MxDV), and end-diastolic velocity (EDV) were also measured in relation to the respiratory cycle. The point of MxDV corresponded to the peak value of the second dicrotic notch in the flow profile. Blood velocity was analyzed by integrating the outer envelope of the maximum velocity values from the accurately obtained flow profile [12–14,20], beat-by-beat, for approximately three successive beat samplings in relation to the 4-s inspiratory and 4-s expiratory phases (the legend for Figure 3). BF was determined by multiplying the cross-sectional vessel area [$\text{area} = \pi \times (\text{vessel diameter}/2)^2$] by average blood velocity.

Heart rate (HR) and mean arterial blood pressure (BP) was monitored continuously using an auricular plethysmography device with oscillometric calibration, with a cuff tourniquet placed on the upper right arm (RadiaPress RBP-100; KANDS, Aichi, Japan). Mean arterial BP was calculated by integrating the BP curve over time, and recorded by computer using the PowerLab® data acquisition system. HR and mean arterial BP were measured beat-by-beat during the inspiratory and expiratory phases in accord with sampling of beat-by-beat blood velocity determinations.

Intraobserver variability

Operator variability was minimized by extensive training with the ultrasonography equipment, using the subjects of the present study. The criterion for quality control of operator technique was to obtain minimum values for the coefficient of variation (CV) of blood velocity and vessel diameter in repeated measurements [12–14]. To reduce operator variability, all measurements were performed by the same person (the first author).

In our previous report, the CV for vessel diameter in the Ao, LFA, and RFA for three repeated measurements was <0.7%, <1.0%, and <1.0%, respectively, and the CV for blood velocity in the Ao, LFA, and RFA for three repeated measurements was <1.1%, <1.3%, and <1.4%, respectively [13]. Therefore, these previous experiments demonstrate that this measurement procedure, when performed by a well trained operator, enables the precise detection of physiological response in blood velocity and vessel diameter with minimal operator variability due to human error.

Statistical analysis

Data were analyzed using multiple analysis of variance (ANOVA) for repeated measures and Fisher's significant difference for post-hoc tests, when comparing more than two groups; the paired *t*-test was used when comparing only two groups. HR, mean arterial BP, peak relative respiratory amplitude, duration of respiratory cycle, blood velocity, and BF obtained for each artery were analyzed between the expiratory- and inspiratory-phases (paired *t*-test) and for sitting and supine positions, as well as between sitting and supine (paired *t*-test) for the inspiratory- and expiratory-phases. A *p* value <0.05 was considered statistically significant. All values are expressed as the mean ± SE.

RESULTS

Hemodynamic parameters and variation in the respiratory cycle

In the preliminary test, vessel diameter in Ao, LFA and RFA were defined as 1.61 ± 0.03 , 0.93 ± 0.02 and 0.95 ± 0.02 cm, respectively. In Table 1, the duration of the expiratory/inspiratory phases was close to the target of 4 s.

Mean arterial BP was no significantly changes between the inspiratory and expiratory phases in the sitting or supine positions; however, HR was significantly lower in the supine than in the sitting position during both the inspiratory and expiratory phases. Furthermore, a significant higher HR during the inspiratory compared with the expiratory phase was seen in the supine but not in the sitting position.

There was no significant difference in HR, mean arterial BP, or duration of respiration over three arterial measurements, with a small CV (<4.5%) in the expiratory and inspiratory phases, for both sitting and supine. Moreover, no significant difference in peak of relative respiratory amplitude over the three arterial measurements was seen in the sitting or supine positions, with a relatively large CV (~16%).

Blood velocity during the respiratory cycle (Figure 4)

Blood velocity in the inspiration was significantly lower than that in the expiration in all three arteries ($P < 0.01$). In particular, a greater reduction in blood velocity was observed in Ao than in FAs. There was no significant difference in blood velocity between sitting and supine at each of the three conduit arteries, in expiration or inspiration. A tendency for higher blood velocity in FAs ($P < 0.15$) at supine than at sitting was not observed in Ao ($P < 0.90$). PSV, MxDV, and EDV in Ao were significantly lower ($P < 0.05$) at inspiration than at expiration in the sitting and supine positions (Table 2).

BF in the three-conduit arteries and BF_{AP} (Figure 5)

BF in the three conduit arteries was significantly lower ($P < 0.01$) in the inspiration than in the expiration. BF_{AP} was significantly lower ($P < 0.01$) in the inspiration than in the expiration at both sitting and supine positions. There was no significant difference in BF among the three conduit arteries or in BF_{AP} between sitting and supine.

DISCUSSION

The major finding of the present study is that blood velocity/BF in the target three conduit arteries (consequently determined BF_{AP}) shows alterations between the inspiration and expiration in both the sitting and supine positions. The fact that BF_{AP} is influenced by respiration contributes further information to the process of BF_{AP} determination.

Alterations in blood velocity caused by variation in the spontaneous respiratory cycle

We demonstrated a difference in blood velocity between inspiration and expiration for the three conduit arteries, with a significant reduction in blood velocity observed in the inspiration compared with that in the expiration. A preliminary study indicated that the vessel diameters of the three target arterial vessels were no different between inspiration and expiration. We subsequently demonstrated that the value of BF_{AP} was lower in the inspiratory than in the expiratory phase at both sitting and supine, during spontaneous shallow normal/natural breathing in a rhythmical 8-sec respiratory cycle.

Previous studies regarding the relationship between venous flow and respiration reported a reduction of BF in the femoral vein following the Valsalva maneuver or in abdominal breathing that increases abdominal pressure [21], as well as during spontaneous thoracic breathing [22] in the supine position. The capacitance of venous vessels versus breathing has well been reported; however, the relationship between respiration and Ao located in the deep region of abdomen, as well as FAs located more superficially, remains unclear.

Based on the simultaneous recordings obtained in the present study, spontaneous breathing appeared to have a direct influence on the transient intra-arterial hemodynamic profile of Ao as well as the FAs (Figure 3), although the duty respiratory cycle was spontaneous with very shallow breathing. Blood velocity in Ao showed a significant reduction ($P < 0.01$) of ~5 cm/sec in the inspiratory phase (24.5 cm/sec sitting, 24.7 cm/sec supine) compared with the expiratory phase (29.3 cm/sec sitting, 29.1 cm/sec supine), with no difference between sitting and

Table 1. Hemodynamic parameters and variables in respiratory cycle.

Measurement phase	Sitting					
	Expiration			Inspiration		
	Ao	LFA	RFA	Ao	LFA	RFA
HR (beats/min)	61.6±2.2	63.3±2.4	64.0±2.4	63.0±1.8	64.6±2.0	64.4±2.1
CV _{HR} (%)	—	3.3±0.6	—	—	2.6±0.4	—
MBP (mmHg)	83.0±2.9	81.5±2.6	81.8±2.7	83.0±2.8	81.5±2.7	81.2±2.8
CV _{MBP} (%)	—	1.3±0.2	—	—	1.3±0.3	—
Duration of respiration (sec)	4.1±0.1	4.1±0.1	4.1±0.1	3.9±0.1	4.0±0.1	4.0±0.1
CV _{DR} (%)	—	3.0±0.4	—	—	4.3±0.7	—
Peak relative respiratory amplitude (%)	—	—	—	17.2±2.4	18.9±2.9	18.8±2.6
CV _{PRRA} (%)	—	—	—	—	14.5±3.0	—
Measurement phase	Supine					
	Expiration			Inspiration		
	Ao	LFA	RFA	Ao	LFA	RFA
HR (beats/min)	56.5±2.3**	57.5±2.5*	57.9±2.2**	58.4±2.0** ^a	59.4±2.0* ^a	60.3±2.2* ^b
CV _{HR} (%)	—	2.3±0.4	—	—	1.7±0.4	—
MBP (mmHg)	84.2±2.4	84.5±2.1	84.7±2.3	83.2±2.3	84.1±2.5	84.7±2.2
CV _{MBP} (%)	—	1.3±0.3	—	—	1.4±0.3	—
Duration of respiration (sec)	4.0±0.1	4.0±0.1	3.9±0.1	4.0±0.1	4.1±0.1	4.1±0.1
CV _{DR} (%)	—	4.3±0.9	—	—	4.4±0.7	—
Peak relative respiratory amplitude (%)	—	—	—	16.3±3.1	16.4±3.0	15.2±3.5
CV _{PRRA} (%)	—	—	—	—	15.8±3.0	—

Ao – upper abdominal aorta; LFA – left femoral artery; RFA – right femoral artery; HR – heart rate; MBP – mean arterial blood pressure; DR – duration of respiration; PRRA – peak relative respiratory amplitude; CV – coefficients of variation (over the three arterial measurements). Statistical significance in HR at supine is stated as * P<0.05, ** P<0.01 versus sitting, and is stated as ^a P<0.05, ^b P<0.001 versus expiration at supine. Values are expressed as the mean ± SE.

supine (Figure 4). In contrast, blood velocity in FAs showed a small reduction (P<0.01) of ~0.8 cm/sec in the inspiratory phase compared with the expiratory phase, in both the sitting and supine positions. This result may be in agreement with the finding of our previous study that BF_{Ao} compared to BF_{FAs} has potentially the largest influence on BF_{AP} [14].

Another finding of the present study was that PSV, MxDV, and EDV in the three conduit arteries change in relation to respiration in both the sitting and supine positions (Table 2). PSV was strongly influenced by the respiratory cycle in Ao as well as FAs, with a decrease recorded during inspiration. It is likely that the reduction of the average beat-by-beat blood velocity value in the three arteries depends largely on a reduction in PSV and partially on MxDV (Table 2; Figure 4); however, there was no change in MxDV (except for RFA in the sitting position) or EDV during inspiration in the sitting or supine positions. We consider that because the peripheral

FAs are located downstream (away from the lower body truncus), they may be less influenced by the alterations in intra-thoracic and intra-abdominal pressure that occur during respiration. This proposal is in agreement with the finding that BF was inhibited in the femoral vein during the 3-sec inspiratory phase, but increased to approximately 500 ml/min during the 3-sec expiratory phase in the supine position [22]. We speculate that mechanical compression related to the degree of breathing affects the transient reduction of BF in the three conduit arteries via alterations in intra-thoracic and intra-abdominal pressure; however, few investigations exist regarding the influence of different respiratory frequencies and amplitude on the hemodynamics of the Ao and FAs.

In contrast, mean arterial BP response showed no marked changes between the inspiratory and expiratory phases in the sitting or supine positions; however, HR was significantly lower in the supine than in the sitting position during both the

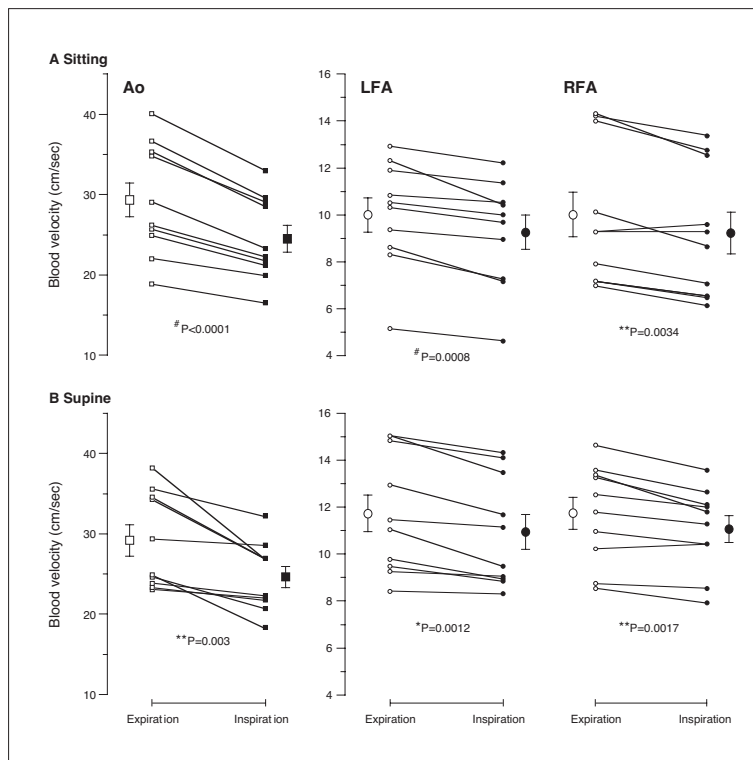


Figure 4. Blood velocity during the respiratory cycle in both sitting and supine positions. Blood velocity was significantly lower in the inspiratory than expiratory phase in Ao, LFA, and RFA at A) sitting and B) supine. * P<0.05, ** P<0.01, # P<0.001 comparison between expiratory and inspiratory phase. Values are expressed as the mean ± SE. The abbreviations see in Table 1.

Table 2. Alterations in flow velocity parameters for each artery during expiration and inspiration, in the sitting and supine positions.

Posture	Sitting						
	Measurement phase	Expiration			Inspiration		
		Ao	LFA	RFA	Ao	LFA	RFA
	Peak systolic velocity (cm/sec)	98.1±6.7	56.9±3.3	51.8±3.6	83.8±5.3**	53.3±2.7*	47.3±3.4#
	Max. diastolic velocity (cm/sec)	28.5±2.6	13.5±1.0	13.7±1.5	22.7±1.8**	13.1±0.7	12.7±1.4*
	End-diastolic velocity (cm/sec)	15.7±1.4	2.8±0.6	3.0±0.7	11.6±0.8*	2.4±0.5	2.7±0.7
Posture	Supine						
	Measurement phase	Expiration			Inspiration		
		Ao	LFA	RFA	Ao	LFA	RFA
	Peak systolic velocity (cm/sec)	111.6±6.4	70.6±4.8	70.5±4.8	95.0±4.0*	65.5±4.8**	64.9±4.2*
	Max. diastolic velocity (cm/sec)	27.4±1.7	16.2±1.2	15.7±1.1	22.5±0.9**	15.5±1.2	15.6±1.2
	End-diastolic velocity (cm/sec)	12.2±1.2	2.2±0.4	2.5±0.2	9.4±0.6*	1.7±0.3	2.3±0.4

Ao – upper abdominal aorta; LFA – left femoral artery; RFA – right femoral artery. Significant reduction in the value of blood velocity parameters during inspiration is indicated as * P<0.05, ** P<0.01, # P<0.001 versus that during expiration, in the sitting and supine positions. Values are expressed as the mean ± SE.

inspiratory and expiratory phases. Furthermore, a significant higher HR during the inspiratory compared with the expiratory phase was seen in the supine but not in the sitting position. This clear difference in HR between the inspiratory and expiratory phases in the supine position may be evidence of respiration-related cardiac vagal tone/vasovagal activity [23,24]. Consequently, the tendency for a slightly higher blood velocity in FA, with lower HR in the supine position, appeared to be caused by the postural effect because the peripheral site is

more strongly influenced by venous return to the heart [25]. The present data, however, showed that postural change has little influence on BF in the three conduit arteries, even if HR response is highly sensitive to the inspiratory or expiratory phase.

Influence of respiration on BF_{AP}

Regarding the physiological significance of the present study, our results showed that respiration-related changes

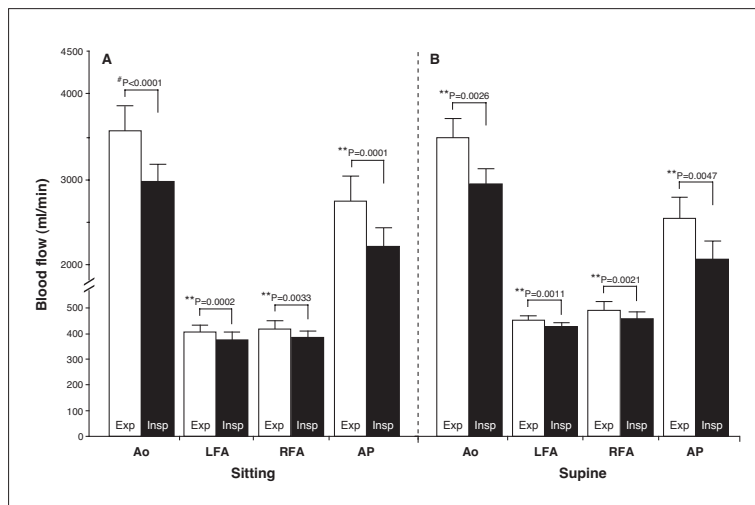


Figure 5. Blood flow in the three conduit arteries and abdominal-pelvic organs during the respiratory cycle, in both sitting and supine positions. Blood flow (BF) was significantly less in inspiration (Insp) compared with expiration (Exp) in Ao, LFA and RFA, in both A) sitting and B) supine positions. Consequently, BF in the comprehensive abdominal-pelvic organs (AP) was lower in inspiration than in expiration, in both the sitting and supine positions. ** $P < 0.01$; # $P < 0.001$. Values are expressed as the mean \pm SE. Other abbreviations see in Table 1.

to the hemodynamics of the three conduit arteries potentially lead to alterations in BF_{AP} . In the present study, the difference in BF_{AP} between inspiration and expiration was approximately 550 ml/min in the sitting position and 480 ml/min in the supine position. In our previous study [12], BF_{AP} showed a reduction of 517 ± 152 ml/min during unilateral limb exercise at a much lower intensity of 2.1 W and 1.4 metabolic equivalents (close to the basal state of 1 metabolic equivalent) under spontaneous breathing. Therefore, the amount of change in BF_{AP} obtained in the present study may be considered to be within the acceptable range at basal conditions. Further investigation of the hemodynamics of BF_{AP} will require evaluation using different frequencies and amplitudes of the respiratory cycle, beyond the limits of flow measurements.

Deep thoracic breathing in inspiration produces rapid acceleration of BF in veins located near the thorax, such as the hepatic vein, the jugular vein, and the inferior vena cava [26], while the blood velocity in these veins is reduced just as rapidly at the start of expiration [27]. The effects of mechanical ventilation with positive end expiratory pressure (PEEP) on systemic hemodynamic or splanchnic perfusion have been examined in animals [28–30]. A higher PEEP-induced increase in lung volume may be marred by an associated increase in thoracic pressure, which could in turn impede venous return, thereby altering systemic hemodynamics and hepatic venous outflow [31]. In animal experiments, portal vein blood velocity and hepatic arterial blood velocity were shown to decrease with PEEP (while preserving blood volume) as a result of a simple increase in the downstream pressure [32]. The present data may be in partial agreement with the theory that respiratory-induced alteration of BF_{AP} occurs with impedance of venous return in the splanchnic area; however, in post-liver-transplantation patients, PEEP did not have the effect of preserving the increase in splanchnic hemodynamics [33]. There remains a lack of information regarding the relationship between inflow (celiac and both mesenteric arteries) and outflow (portal and hepatic veins) in the splanchnic organ circulation.

A previous study stated that higher values of venous outflow are found in the hepatic and portal veins in the supine rather than upright position due to the effect of gravity [26];

however, there is a lack of information regarding the arterial inflow of the splanchnic circulation. In contrast, in the present study, the reduction of BF_{AP} in the inspiratory phase was similar between sitting and supine, and thus no postural effect on BF_{AP} was seen. Because the splanchnic circulation is intrinsically susceptible to the adverse effects of hydrostatic force [26,34], redistribution due to postural change between sitting and supine may differ between venous and arterial sites.

Methodological considerations and limitations

BF_{AP} compared with previous findings

In the present study, mean BF_{AP} was 2765 ± 303 ml/min for the expiratory phase and 2213 ± 222 ml/min for the inspiratory phase in the sitting position, and 2539 ± 253 ml/min for the expiratory phase and 2059 ± 215 ml/min for the inspiratory phase in the supine position. Previous studies [35] showed that the average splanchnic BF, including that of the celiac trunk, mesenteric arteries, is approximately 1500 ml/min, corresponding to 20–30% of cardiac output. The sum of the BF values in the two renal arteries is approximately 1000–1200 ml/min, which corresponds to 20% of cardiac output [36]. Another study reported BF as 1400 ml/min in the liver, gastro-intestine, and spleen, and 1100 ml/min in the kidney [37]. The values for the sum of BF in the major “splanchnic” and the “two renal arteries” reported in previous studies are similar to the range of BF_{AP} obtained in the present study. Furthermore, our previous work found a mean BF_{AP} value of 2630 ± 153 ml/min in 18 male participants (aged 20–38 years) [12], while BF_{AP} was 2078 ± 495 (SD) ml/min in 40 male participants (aged 19–39 years) in a different study cohort [13]. The present BF_{AP} lies within the acceptable range indicated by the above-mentioned previously validated values.

The subjects of the present study were 50 healthy men (age range, 20–39 years); therefore, the hemodynamic relationships obtained in the present study may not include the effects of aging beyond 40 years. The sample size in the present study may not be large enough to determine the standard value of BF_{AP} among different ages to see the influence of respiration and posture; however, it was sufficient to indicate

the physiological significance regarding to the influence of respiration (interplay between inspiration and expiration) and posture on BF_{AP} . In generally, arteriosclerosis may occur in moderate aging due to circulatory dysfunction. Further investigation of the above-mentioned hemodynamic relationship regarding to heart failure, hypertension, diabetes, smoking effects is required before the method can be applied in the clinical session.

Measurement process for the three conduit arteries as components of BF_{AP}

A technical limitation of the procedure used in the present study is that measurement of the three conduit arteries was not performed simultaneously (i.e., they were obtained at different time points) by the same operator. The most robust process for obtaining the various arterial measurements is during the shortest possible time interval. The magnitude of blood velocity can be influenced by variations in HR or BP, or by operator variability.

If HR and BP fluctuate widely while the three arterial measurements are obtained, the resulting BF_{AP} would be potentially over- or under-estimated; however, in the present study, BF_{AP} lies within a reliable range because variability in HR and mean arterial BP was less than 4.5% of CV, as a steady state.

BF_{AP} may not completely reflect BF to the splanchnic area because comprehensive BF_{AP} includes BF in both renal arteries, the internal iliac artery, and some minor arteries except for BF in the original splanchnic organs. The role of the magnitude of BF in the above-mentioned arteries and in the original splanchnic organs in terms of blood redistribution during respiration remains unknown.

Variable respiratory cycle

It may not be possible to completely exclude motion of the probe during the respiratory cycle, unless the subject performs breath-holding. However, the motion is negligible, and is insufficient to move the sampling point out of the target vessel during spontaneous breathing.

Although the subjects of the present study were well trained to perform the target respiratory cycle, the CV of the peak relative respiratory amplitude over three arterial measurements was slightly large at ~16%. These fluctuations are in agreement with the minimum variations for voluntary active repeated motion reported in a previous human study [38]. Furthermore, comparison between the measured values in the three arteries and BF_{AP} were evaluated under conditions of no significant difference in the peak of relative respiratory amplitude value among the three arterial measurements, as well as between sitting and supine. Respiratory rhythm (duration of each inspiratory – expiratory phase) was constant, at 4 sec. Thus, the values obtained in the present study may be considered acceptable in terms of respiratory and postural effects.

CONCLUSIONS

The present study demonstrated that changes in blood velocity in the three conduit arteries between expiration and inspiration may potentially indicate alterations in BF_{AP} and are only minimally influenced by posture. We speculate

that this finding could be due to mechanical compression of vascular flow perfusion in comprehensive BF_{AP} or via the vasovagal response. Evaluation of BF_{AP} hemodynamics in the three conduit arteries should take respiratory effects into account. Finally, the organ perfusion or blood supply depends on many factors which are the mean arterial BP and/or cardiac index, or as surrogate parameter the central venous saturation used in the clinical session. The impact of respiration or posture effects may potentially be the indicator for the determination of adequate organ perfusion, and consequently signs of impaired organ perfusion.

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