Assessment of flow mechanics in the lower extremity venous system

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ABSTRACT

Background: The Reynolds number (R_e) is a dimensionless parameter that describes fluid flow mechanics. Veins are compliant and collapsible vascular conduits that can accommodate large volume changes in response to small pressure changes. However, only sparse information is available about flow parameters such as the R_e in the venous system.

Methods: Bilateral duplex ultrasound examination of 15 healthy volunteers (30 limbs) was performed before and after exercise (four flights of stairs) of the veins of the lower extremity (left and right sides) and inferior vena cava. These volunteers had been confirmed to not have any signs or symptoms of lower extremity venous disease via focused history and physical examination findings.

Results: Most of the volunteers were women (73%). Their mean age was 37 ± 12.8 years. The R_e was highest in the inferior vena cava among all the veins examined (470 ± 144 before exercise and 589 ± 205 after exercise; $P = .04$). The association between the change in R_e before and after exercise and the specific vein examined was also significant for the right and left external iliac veins, right and left common femoral veins, right and left profunda femoris veins, right and left femoral veins, and right common iliac vein. Resistance and velocity maps for the lower extremity venous system were also created. The velocity increased and the resistance decreased as one moved up the venous tree toward the right atrium.

Conclusions: The R_e increased for most of the lower extremity veins after exercise in our healthy volunteers. However, the critical value for turbulent flow was not reached despite the exercise. (J Vasc Surg Venous Lymphat Disord 2022;■:1-8.)

Keywords: Fluid; Inferior vena cava; Iliac vein; Resistance; Reynolds number; Turbulence; Velocity

Arteries and veins are fundamentally different from each other.[1,2] Veins are compliant and collapsible vascular conduits that can accommodate large volume changes in response to small pressure changes. The fluid dynamics of collapsible tubes were described in detail by Shapiro[3] several decades ago. According to Shapiro,[3] "the mechanics of flow is closely coupled to the mechanics of the tube."

The Reynolds number (R_e) is a dimensionless parameter that describes fluid flow mechanics (simplistically, laminar vs turbulent flow). It is a ratio of the inertial forces to the viscous forces within a fluid. A lower R_e reflects laminar flow—whereby viscous forces are more dominant and flow is smoother. A parabola can be formed of these velocity profiles. When inertial forces dominate, the R_e will be higher and flow will be considered turbulent. In general, a R_e <2300 indicates laminar flow and a R_e >4000, turbulent flow. Between 2300 and 4000, the R_e will indicate transitional flow (ie, a mixture of turbulent and laminar flow).[4]

Much of the prior research has focused on the fluid dynamics in the arterial system, including the aorta.[5] However, not much is known about the flow parameters, including the R_e, in the venous system. In the past, it was hypothesized that exercise could cause the R_e in the venous system to exceed 2300.[3] To enhance our understanding of the flow mechanics of the lower extremity venous circulation, we investigated the R_e in healthy volunteers without any signs or symptoms of venous disease. We also correlated the R_e with factors such as age, body weight, gender, and body mass index (BMI). In addition, we investigated whether in healthy individuals, the "lower critical value" (ie, a R_e of 2000) in the venous system would be exceeded by physiologic activities simulating vigorous exercise. In addition, we created velocity and resistance maps for the lower extremity venous system.

METHODS

Type of research study. We performed a single-center, prospective, observational study in October 2021. All data were contemporaneously entered and analyzed. All the volunteers provided written informed consent for

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Author conflict of interest: S.R. has a U.S. patent for IVUS (intravascular ultrasound) diagnostics and a U.S. patent for iliac vein stent design.

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their participation in the study. The institutional review board approved the present study.

Inclusion and exclusion criteria. A duplex ultrasound examination of 15 healthy volunteers (30 limbs) was performed of the inferior vena cava (IVC) and the following veins on both sides (left and right): common iliac vein (CIV), external iliac vein (EIV), common femoral vein (CFV), profunda femoris vein, femoral vein, popliteal vein, posterior tibial veins, great saphenous vein, and small saphenous vein. These volunteers had been confirmed to not have any signs or symptoms of lower extremity venous disease via focused history and physical examination findings.

Calculation of R_e. The R_e was derived using the following equation:

$$R_e = \frac{(\bar{v} \cdot D \cdot \rho)}{\eta}$$

where v is the mean velocity of flow (cm/s); D is the mean hydraulic depth (cm); and ρ is the density of the fluid (g/cm^3), taken as 1.054.[6] Nu (ŋ) refers to the dynamic viscosity (dynes·s/cm^2; value, 0.04 poise,[7] which is more accurate for humans)[6] and is the fluid's resistance to the external force applied to it.[8] Nu/ρ is known as the kinematic viscosity. It is the measure of a fluid's innate resistance to flow when no external force, except for gravity, is weighing down on it.

The centimeter-gram-second system unit of kinematic viscosity is known as stokes. The kinematic viscosity of blood at a body temperature of 38°C is ~3.8×10^{-2} stokes.[8,9] For the purposes of calculating the R_e, we assumed a constant viscosity and density (ie, Newtonian and noncompressible fluid and cylindrical vessel shapes).[10]

Calculation of resistance. Resistance was calculated using the following equation: resistance = (8 × ŋ × L)/(π × r^4), where Nu (ŋ) is the dynamic viscosity (dyne·s/cm^2; value, 0.04 poise in humans)[6,7]; L is the length of the vessel; and r is the radius of the vessel. The unit for resistance is dynes·s/cm^5. For the resistance calculations, the lengths of the veins used were those described by Ouriel et al.[11] Velocity will increase and resistance decrease as one moves up the venous tree. Velocity is proportional to πr^2, and resistance is proportional to πr^4.

Exercise protocol. A duplex ultrasound examination was performed for each volunteer initially and immediately after they had been asked to climb four flights of stairs to simulate vigorous exercise.

Other parameters. The other parameters that were recorded included age, gender, weight, height, and BMI of the volunteers.

ARTICLE HIGHLIGHTS

- **Type of Research:** A single-center, prospective study
- **Key Findings:** The Reynolds number was investigated in the lower extremity venous system before and after exercise of healthy volunteers without any signs and symptoms of venous disease. A critical value for turbulent flow was not reached in the venous system despite the exercise.
- **Take Home Message:** The Reynolds number increased in most lower extremity veins after exercise in healthy volunteers but did not reach the critical value for turbulent flow.

Duplex ultrasound examination technique. The volunteers were examined in the supine position immediately before and after cessation of exercise. The technique used has been described previously.[12,13] A color duplex ultrasound system (Logiq 9; GE Medical Systems, Waukesha, WI) was used. A 6-Hz curved probe and 9-Hz linear probe with a 60° angle of insonation were used for the examination of the lower extremity venous system. B mode/B flow/color flow images were used to visualize vein lumen and flow channel and obtain measurements of the diameter at the widest point. Confirmation of this, when possible, was obtained in the transverse view.[12] The mean velocity in the veins was also measured.

All the volunteers had undergone the ultrasound examinations using the same uniform protocol. Each scan required ~20 minutes. The right side was scanned before the left, and larger veins were scanned before smaller veins. Finally, the deeper veins were examined before the superficial veins. Usually, the hemodynamic cardiovascular changes after vigorous exercise will persist for ≥10 to 20 minutes and, hence, were captured in the volunteers using this uniform protocol.

Statistical analysis. Statistical analysis was performed using a commercially available statistics program (Prism software; GraphPad, San Diego, CA). Where appropriate, a *t* test or χ^2 test was used for analysis. The Spearman rank correlation coefficient was used to assess the statistical dependence between the variables (eg, age, BMI, gender, height, weight) and the change in the R_e from before to after exercise. $P < .05$ was considered to indicate statistical significance.

RESULTS

Demographic data

We included 15 volunteers (30 limbs) without any preexisting signs or symptoms of venous disease. Most of the volunteers were women (73%). Their mean age was 37 ± 12.8 years (Table I).

Table I. Demographic data for healthy volunteers (N = 30 limbs)

Variable	Value
Age, years (range)	37 ± 12.8 (23-77)
Male/female ratio	2:5
BMI, kg/m^2	26.9 ± 5.1
Weight, kg	77.7 ± 18.3
Height, cm	168.8 ± 9.9

BMI, Body mass index.
Data presented as mean ± standard deviation, unless noted otherwise.

Association between change in R_e and venous segment

The association between the R_e before and after exercise and the specific vein examined by ultrasound is shown in Table II for right-sided veins and Table III for left-sided veins. The association was significant for the bilateral EIVs, bilateral CFVs, bilateral profunda femoris veins, bilateral femoral veins, and right CIV. Increments were also noted between the R_e values before and after exercise for the remaining veins; however, the differences did not reach statistical significance. The mean R_e for the IVC before and after exercise was 470 ± 144 and 589 ± 205, respectively ($P = .04$).

Spearman's rank correlation coefficient

The Spearman rank correlation coefficient was assessed for the change in the R_e for specific vein segments between the pre- and postexercise states and factors such as age, BMI, weight, height, and gender. These associations for the four larger deep veins (IVC, CIV, EIV, and CFV) are shown in Supplementary Figs 1-4 (online only).

Age. For age, the correlation was significant only for the profunda femoris vein ($r = -0.52$; $P = .002$).

Weight. For weight, the correlation was significant only for the popliteal vein ($r = 0.43$; $P = .02$).

Table II. Association of Reynolds number (R_e) before and after exercise and right-sided veins

Right-sided vessel	R_e before exercise	R_e after exercise	*P* value
CIV	360 ± 112	524 ± 132	**.001**
EIV	333 ± 70	553 ± 226	**.003**
CFV	239 ± 98	514 ± 296	**.0001**
FV	136 ± 60	198 ± 64	**.0004**
Profunda femoris	135 ± 43	213 ± 91	**.0006**
Popliteal	94 ± 38	117 ± 60	.1
Posterior tibial	29 ± 14	27 ± 15	.8
GSV	39 ± 24	45 ± 33	.8
SSV	20 ± 14	18 ± 14	.6

CFV, Common femoral vein; *CIV,* common iliac vein; *EIV,* external iliac vein; *FV,* femoral vein; *GSV,* great saphenous vein; *SSV,* small saphenous vein.
Data presented as mean ± standard deviation.
Boldface *P* values represent statistical significance.

Height. For height, the correlation was not significant for any venous segment (data not shown).

Body mass index. For the BMI, the correlation was significant for the EIV ($r = 0.37$; $P = .04$) and popliteal vein ($r = 0.39$; $P = .03$).

Gender. For gender, the correlation was not significant for any venous segment (data not shown).

Diameters

The diameters measured using duplex ultrasound in various venous segments before and after exercise were as follows: IVC, 9.8 ± 2.1 mm before exercise and 12.1 ± 2.5 mm after exercise; CIV, 10.8 ± 2.1 mm before exercise and 11.5 ± 1.8 mm after exercise; EIV, 12.6 ± 1.9 mm before exercise and 13.4 ± 1.8 mm after exercise; and CFV, 11.7 ± 1.6 mm before exercise and 11.9 ± 1.6 mm after exercise. These values were less than those predicted using the scaling rule. Young's scaling law provides details of the relationship between parent and daughter branching diameters. According to this law, the parent/daughter branching diameter ratio should be 1.26:1.

Resistance

The calculated resistance in the various venous segments was mapped (Supplementary Fig 5, online only). Resistance appeared to decrease as we moved up the venous tree and was proportional to πr^4 (Fig).

Velocity

The measured velocities in the various venous segments were also mapped (Supplementary Fig 5, online only). Velocity appeared to increase as we moved up the venous tree and was proportional to πr^2.

DISCUSSION

Reynolds number. Sir Osborne Reynolds, an engineer and physicist, studied a stream of dye in a long cylindrical tube. He noted that the motion of the fluid was laminar until the rate of flow had increased to a critical value, at which point it became turbulent. The critical value for long straight tubes would be different than the critical value of stenosed nonlinear tubes.[14] However, the nature of flow in vivo is complex owing to other vascular factors such as compliance.[5] The relationship between the area (or interchangeably volume) and the transmural pressure difference (tube law) describes the association of structural mechanics to fluid mechanics.[15] The pressure–area curve has a sigmoid configuration. Velocity changes will result in pressure changes, and pressure changes, will, in turn, cause area changes. These area changes will produce velocity changes.[15] At a positive transmural pressure difference, the tube will be inflated. In contrast, the tube will be partially collapsed with a negative transmural pressure difference. Because the curve is nonlinear, the collapsible tube flow is likely to be complex. In experimental models, friction appeared to be the dominating factor when the conduit was full

(Poiseuille's law) vs inertia dominating the flow when the conduit was collapsed.[3,16]

Investigation of turbulent flow in the human venous system is important because turbulent flow could underlie several pathophysiologic processes such as thrombosis, intravascular hemolysis, and, possibly, peripheral venous hypertension.[4] For the venous system, information on flow dynamics is relatively sparse compared with that available for the arterial system. As a first step, we attempted to establish the R_e in a subset of 15 healthy volunteers without signs or symptoms of venous disease and gather some data on other flow parameters such as the velocity and resistance in the venous tree. Most historical authorities on the subject (eg, Helps and McDonald,[6] Shapiro,[3] Moody,[17] *Strandness* and Sumner[18]) have all agreed that the flow in the venous system is laminar unless venous collapse has occurred. In the latter circumstance, flow likely becomes turbulent. Moody's diagram shows the Darcy-Weisbach friction factor plotted against R_e values for various relative roughness values.[17] It divides the flow into two regions: laminar flow and turbulent flow, with a transition zone in between. We have shown that with exercise, the flow in the venous system will not become turbulent according to these standards. The average R_e was <500 for the lower extremity veins examined despite the exercise, a value too low to be considered turbulent flow. Hence, it seems unlikely that the flow in the veins would become turbulent under physiologic conditions.[3,6,17]

The R_e was chosen as a hemodynamic surrogate for the present study because relatively little is known about it in the venous system. Burton[19] measured the velocity in the IVC at rest and exercise and showed that it increases with exercise. However, he did not calculate the R_e in his investigations.[19]

Young's scaling rule. Several scaling models have been described in the literature, including Young's scaling rule and Murray's law.[20] However, the role of these scaling models has not been well established in the venous system.

Investigation of vascular branching across multiple vascular systems in the body has shown a parent to daughter branching with a diameter ratio of 1.26:1. This scaling rule (Young's scaling rule) provides a basis for efficient branching in the vascular system to maximize flow and minimize the expenditure of energy.[12,21] The pioneering work by Huo and Kassab,[21] Wu et al,[22] and Kassab[23] noted differences between the proximal and distal coronary sinuses when this rule was applied, with the last six branches not conforming to Young's scaling rule. The investigators explained this anatomic arrangement by the teleological need to preserve the terminal velocity in the coronary sinus.[21-23]

The venous velocity increases as one moves from the daughter branches to the larger parent veins for two reasons: (1) pressure changes ("a small gradient develops") as the veins approach the right atrium; and (2) increases in the venous caliber. The IVC would be expected to have the largest R_e compared with other smaller caliber veins in the lower extremity because of the higher mean velocity, proximity to the heart, and greater caliber.[6] We found this in our investigation of the R_e in healthy volunteers, with the IVC demonstrating the highest R_e of all the veins studied. In our subset, the values approached >500 after exercise in the IVC but had never exceeded the lower critical threshold of turbulent flow despite the vigorous exercise.

Table III. Association of Reynolds number (R_e) before and after exercise and left-sided veins

Left-sided vessel	R_e before exercise	R_e after exercise	*P* value
CIV	305 ± 135	389 ± 100	.06
EIV	266 ± 92	407 ± 202	**.001**
CFV	245 ± 102	339 ± 203	**.03**
FV	116 ± 25	159 ± 53	**.002**
Profunda femoris	121 ± 42	163 ± 63	**.0001**
Popliteal	76 ± 29	97 ± 40	.07
Posterior tibial	29 ± 10	28 ± 13	.4
GSV	27 ± 11	24 ± 13	.3
SSV	13 ± 7	13 ± 6	.5

CFV, Common femoral vein; *CIV,* common iliac vein; *EIV,* external iliac vein; *FV,* femoral vein; *GSV,* great saphenous vein; *SSV,* small saphenous vein.
Data presented as mean ± standard deviation.
Boldface *P* values represent statistical significance.

Resistance decreases as one moves from the daughter branches to the larger parent veins. The pressure gradients across the venous segments will generally be small. In addition, the pressure decay was only ~4 mm Hg when moving from the foot to the heart. A scaling factor of ~1:1.2 is all that is needed to keep resistance constant as one moves up the venous tree. However, the scaling factor needed to keep velocity constant will actually be ~1:1.4. Thus, if two tributaries of 2 cm each (area, 314 mm^2) join, the parent vessel should have a diameter of 2.8 cm to maintain the combined area and velocity constant. This scaling factor of 1:1.4 is more than that predicted by Young's scaling rule (1:1.26). Thus, the velocity must accelerate as one moves up the venous tree. At the level of the capillaries or microcirculation, the velocity will be nearly zero, and all the energy present will be in the form of pressure. The value for the IVC appears to be closer to Young's scaling ratio of 1:1.2, measuring ~18 to 24 mm in diameter.

Diameters. We have previously reported that the minimum diameters and stent sizes needed to adequately decompress and reduce peripheral venous hypertension from chronic iliofemoral venous obstruction are as follows:

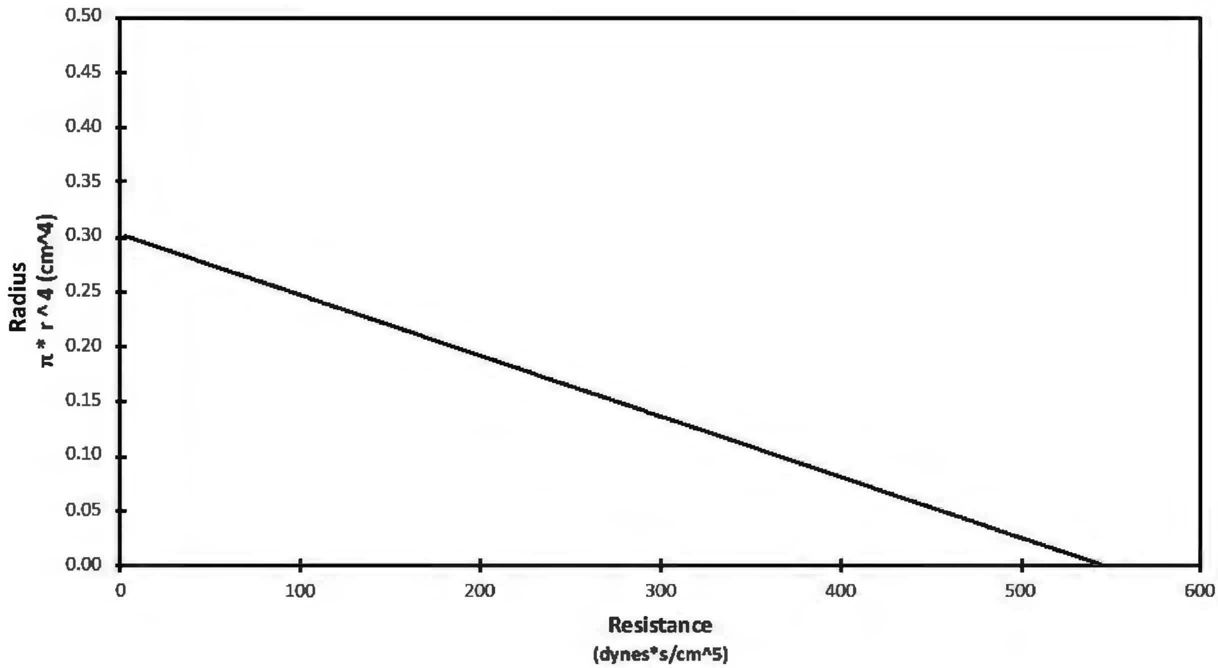

Fig. Relationship between resistance and radius. The x-axis shows resistance (dynes·s/cm^5), and the y-axis shows the radius πr^4 (cm^4). Resistance was proportional to πr^4.

IVC, 18 to 24 mm; CIV, 16 mm; EIV, 14 mm; and CFV, 12 mm.[12] These sizes were derived using intravascular ultrasound (IVUS) planimetry and flow equations such as the Poiseuille equation in nondiseased venous segments in healthy volunteers. We have also demonstrated previously that ultrasound will underestimate the true diameters of venous segments compared with IVUS.[24] Additionally, silent iliac vein stenosis can occur in a significant proportion of the population and the pathology of deep venous disease is permissive, as discussed further in the next sections.[12]

Supercritical and subcritical flow. Supercritical flow occurs when the flow velocity is greater than the critical or phase velocity (which transmits pressure information upstream) in partially collapsed tubes.[25] In supercritical flow, all velocity will travel downstream without change. This is different than subcritical flow, in which the flow velocity is less than the critical or phase velocity. Tube collapse occurs when the velocity equals the wave speed. The tube will re-expand at the "elastic jump" from supercritical flow to subcritical flow.[3] A flow limitation is also a theoretical possibility whereby the transition between supercritical and subcritical flow does not occur even with the help of the "elastic jump," likely when the flow rate is too large.[26] The supercritical and subcritical phase velocity will remain constant if the conduit caliber remains the same. Another point to remember is that supercritical flow has historically not been considered to be laminar flow. By extrapolation, supercritical flow would be expected to have a R_e representative more of turbulent flow than of laminar flow. Shapiro[3] showed that flow can oscillate between supercritical and subcritical depending on a number of factors such as stenosis, compliance, Starling pressure, and outflow pressure.

In the IVC, flow has historically been believed to be supercritical. We noted the R_e in the IVC was higher than that in the other veins but still lower than the critical R_e for turbulent flow despite exercise. Moreover, the number was much lower than that reported for different parts of its arterial counterpart, the aorta (arch and ascending and descending segments, often with a Re of ~3400-4500).[5] For the aorta, strenuous exercise has been postulated to increase the R_e by as much as 10-fold.[27] Therefore, it would appear that in the IVC, the flow is largely laminar unless other factors exist. These could include (1) phasic fluctuations, including backflow; (2) extrinsic distortion of the vessels; and (3) the conditions of flow at the junctions.[4] Under physiologic conditions, these factors will be steady and will not cause major turbulence in venous flow. Based on dye injections performed in animal models (rabbits) several decades ago, laminar flow was found close to the wall of the vessel in the vena cava but a much smaller zone representative of disturbed flow was present further in the middle of the venous conduit.[7] The latter might represent a vortex disturbance zone.[6]

R_e and exercise. Exercise produces changes in flow mechanics, as indicated by the changes in the R_e, in the bilateral EIVs, bilateral CFVs, bilateral profunda femoris veins, bilateral femoral veins, and right CIV. It is known that, at the least, the profunda femoris vein plays an important compensatory role in conditions that cause occlusion of the femoral vein (eg, acute thrombotic occlusion) through an axial transformation phenomenon.[28] Exercise might simulate a more physiologic response than will thrombotic occlusion, which causes recruitment of the profunda femoris vein (in addition to other veins) to aid in the increased aggregate volumetric venous outflow from the lower extremity.

Left iliac vein compression has been noted in many asymptomatic individuals. The landmark paper on this subject by Kibbe et al[29] in 2004 showed left CIV compression as being frequently observed in asymptomatic individuals. We have previously reported that the pathology of iliac venous disease is permissive (ie, a second insult will usually be needed in individuals with the condition [previously "silent"] to destabilize the venous homeostasis and cause symptoms to develop [eg, infection, thrombosis, reflux]).[30] A second, important consideration is that lesions such as iliac vein compression will usually be subsegmental and will typically cause a localized flow disturbance that does not extend beyond the lesion. In accordance with the description by Labropoulos et al[31] in 2007, a peak vein velocity ratio of >2.5 across the stenosis is the best criterion to use for the presence of a pressure gradient of ≥3 mm Hg. The presence of post-stenotic turbulence will increase the diagnostic confidence but not the accuracy of this finding. We did not specifically interrogate for iliac vein compression in the present study. However, it is possible that could explain why no association was found between the left CIV and the change in the R_e number from before to after exercise.

An abrupt increase in velocity was noted in the CFV after exercise (Supplementary Fig 5, online only). However, we did not have a good explanation for this anomaly. Computational fluid dynamics in the future might provide an explanation for this phenomenon. A few explanations are possible, including that phasicity could have a role. We have previously shown that differential phase polarity will be seen between the lower limb veins and the IVC.[32] Also, it could be explained by the Starling resistor mechanism whereby the starling resistor acts as a stenosis.[33] In 1966, Stegall[34] reported higher pressures in the IVC than in the femoral vein before and after exercise. Abdominal muscle contraction has also been postulated to have a role in this phenomenon.[18,33]

Changes in IVC geometry. For the IVC, an increase in the R_e was noted after exercise, and the association was statistically significant ($P = .04$). In a prior study, serial contrast-enhanced computed tomography scans of 30 trauma patients were analyzed during hypovolemic (at admission) and fluid-resuscitated states. Adequate resuscitation leading to repletion of the intravascular volume caused the volume of the infrarenal IVC to increase more than twofold. The expansion of the IVC was noted to be anisotropic such that the minor axis had expanded up to five times, although the major axis had not changed as significantly.[35]

Murphy et al[36] studied the infrarenal IVC during the normal respiratory cycle using IVUS in 10 patients. The mean IVC diameter in the short and long axes was 14.3 ± 4.1 mm and 23.2 ± 3.5 mm, respectively. The IVC geometry changed anisotropically, with a 36% change in the short axis during a Valsalva maneuver.[36] We have shown that the diameter of the mid-abdominal IVC will increase by 32% and its lateral pressure will decrease during inspiration.[32] Grant et al,[37] using color duplex ultrasound, reported that the diameter of the IVC was at its maximum at the end of inspiration.

The work by Hall[38] on the quantitative aspects of venous pressure in dogs showed a dramatic decrease in pressure from the abdomen to the chest. Guyton and Greganti[39] also showed that the right atrial pressure is the steadiest pressure despite postural changes. However, the findings from the canine models reported by Guyton and Adkins[40] should be extrapolated to humans with caution because dogs are thoracic breathers (primary role for the thoracic pump) compared with humans, who are abdominal breathers (primary role for the abdominal pump). Also, it has been believed that veins, including the IVC, will completely collapse during the respiratory cycle.[40] However, flow in the IVC is always present, and, with IVUS, we have shown that it does not completely collapse at any point during the respiratory cycle.[32] When the diaphragm descends during inspiration, the abdominal pressure increases and the velocity should decrease, and the caliber of the IVC should also decrease. However, the effect of external pressure on the tethered portions of the IVC (eg, retrohepatic IVC) is not exactly known and makes the relationships complex. There might be less luminal variation and changes in pressure and volume in the IVC because of these points of fixation. We have noted that the IVC volume paradoxically increased with inspiration, which might result from the accordion-like foreshortening of the IVC with a caliber increase during its passage through the diaphragmatic caval hiatus. No doubt exists that the IVC is the source of phasicity in the venous system. However, the pressure–volume changes in the IVC appear to be complex, because the venous system is a dynamic open flow system. External positive pressure will cause the velocity to decrease; however, the transmural pressure has not shown significant changes in in vitro models.[41] The aspect ratio of the veins changes such that the vertical diameter will decrease more than does the transverse diameter.[16] With a change in the aspect ratio, deformation in the luminal area of the veins might perhaps lead to the flow becoming more turbulent.[16]

Study limitations. The measurement of values used to compute the R_e via duplex ultrasound could have underestimated the true vessel dimensions.[42] Inherent difficulty exists with ultrasound when measuring the diameter of relatively collapsed venous structures. The volunteers were asked to climb four flight of stairs to simulate vigorous exercise; however, the amount and type of exercise had been arbitrarily decided. This exercise routine was not compared with a treadmill test or any other exercise routine. However, the treadmill test itself is an arbitrary test with its own set of limitations. Also, the volunteers were not asked to fast for the present study. Therefore, hydration status was a variable not measured in our study. The examination time and sequence were unavoidable variables; however, they were likely present for each volunteer. In addition, we did not measure the renal vein, hepatic vein, and hypogastric vein inflow in the present study.

As per Shapiro,[3] a tube is an analog for a river. D refers to the mean hydraulic depth, which is defined as the cross-sectional area divided by the perimeter. Because veins are slightly elliptical tubes ("minor" ellipse), the mean hydraulic depth is applicable to them. However, for the purposes of calculation, the veins were assumed to be circular (πr^2). This likely introduced a diameter error of ~10%, which, in turn, would result in a R_e error of 10%. In biologic measurements and systems, a variability of ≤20% has generally been considered acceptable. This R_e error is well within that range. In addition, to change Poiseuille flow from laminar to turbulent, a 300% to 400% increase in the R_e would be required. A 10% error would not result in such a change.

In addition, as previously reported by other investigators, our findings are limited by the R_e itself, which was originally defined for laminar flow in a straight pipe and not for dynamic blood flow in vessels such as veins.[5] Finally, it is important to remember that the critical value for the R_e was experimentally derived and heavily reliant on the conditions of the experiment itself. Nevertheless, we have provided an important physiologic reference for the venous system. The R_e is useful in the calculation of multiple other hemodynamic derivatives. As a basic feature of venous flow, the R_e might be able to provide some information on iliac venous stenosis in the future. More morphometric and flow data from the venous system are needed to better understand the flow dynamics.

CONCLUSIONS

In our study, the R_e had increased for most of the lower extremity veins (both superficial and deep) after exercise in healthy volunteers. However, the critical value for turbulent flow was not exceeded despite the exercise. The velocity increased and resistance decreased as we moved up the venous tree from the smaller to larger branches.

AUTHOR CONTRIBUTIONS

Conception and design: TS
Analysis and interpretation: TS, TP, WW, SR
Data collection: TP, WW, SR
Writing the article: TS, TP, WW, SR
Critical revision of the article: TS, TP
Final approval of the article: TS, TP, WW, SR
Statistical analysis: TP, WW
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Overall responsibility: TS

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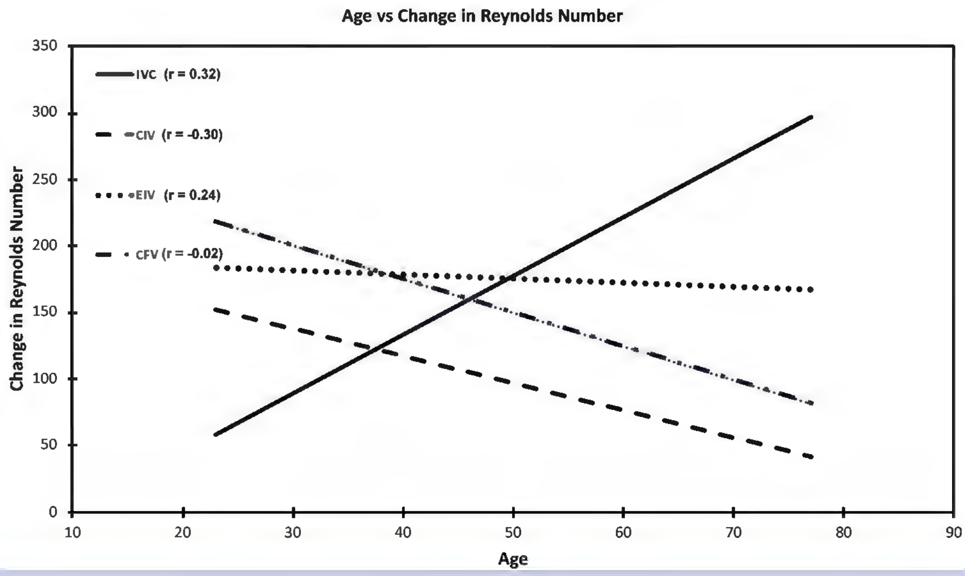
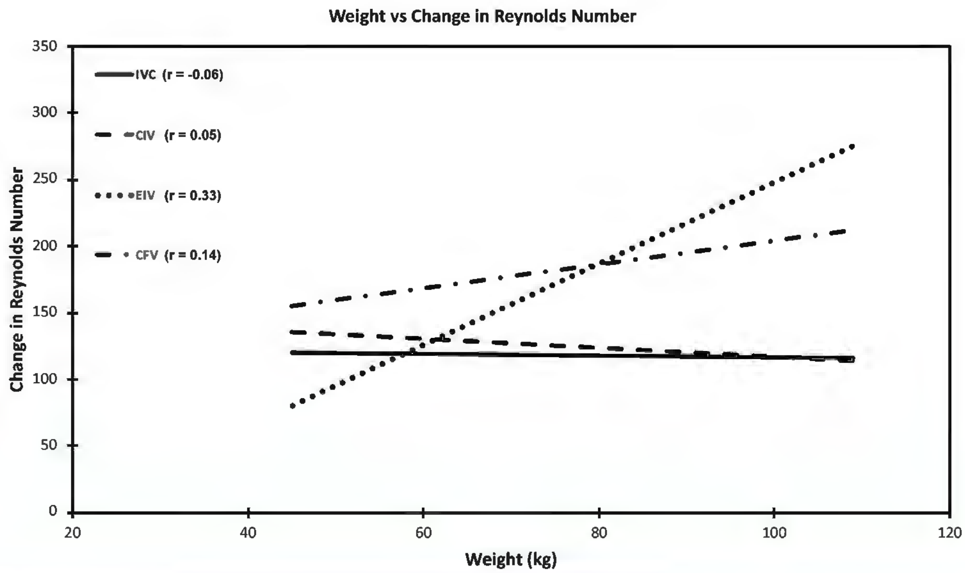
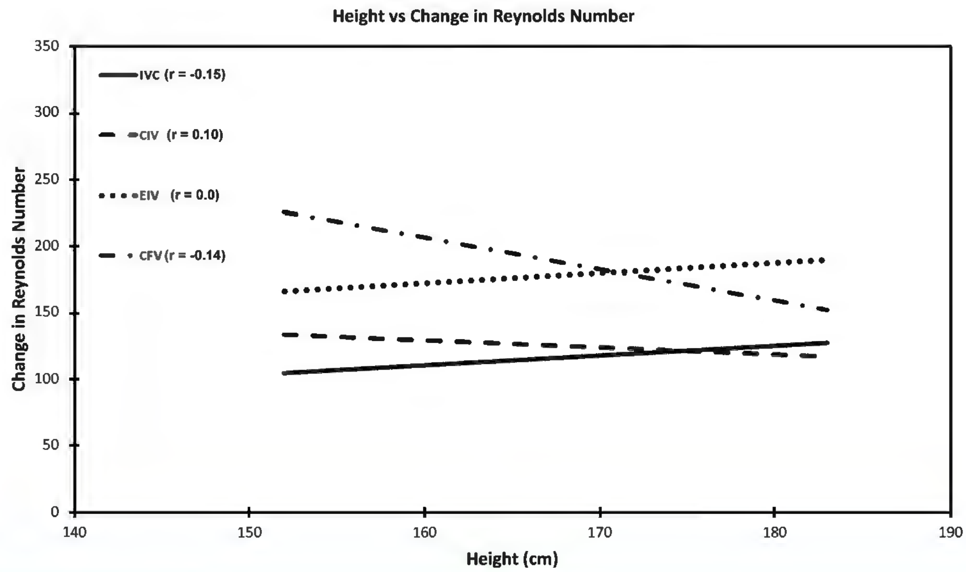


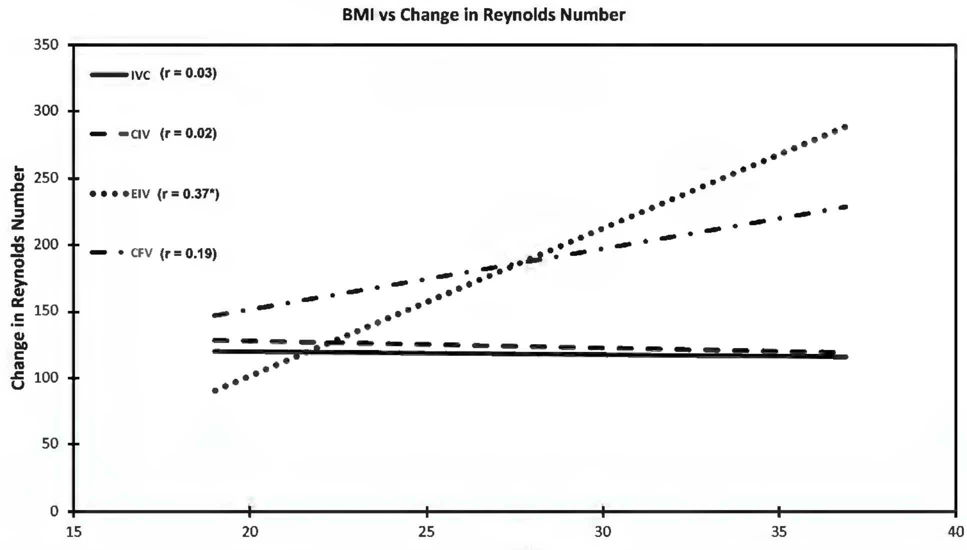
Supplementary Fig 1 (online only). Spearman correlation (*r*) for change in Reynolds number (R_e) before and after exercise for four veins (inferior vena cava [IVC], common iliac vein [CIV], external iliac vein [EIV], common femoral vein [CFV]) and age (IVC: $r = 0.32$; $P =$ NS).



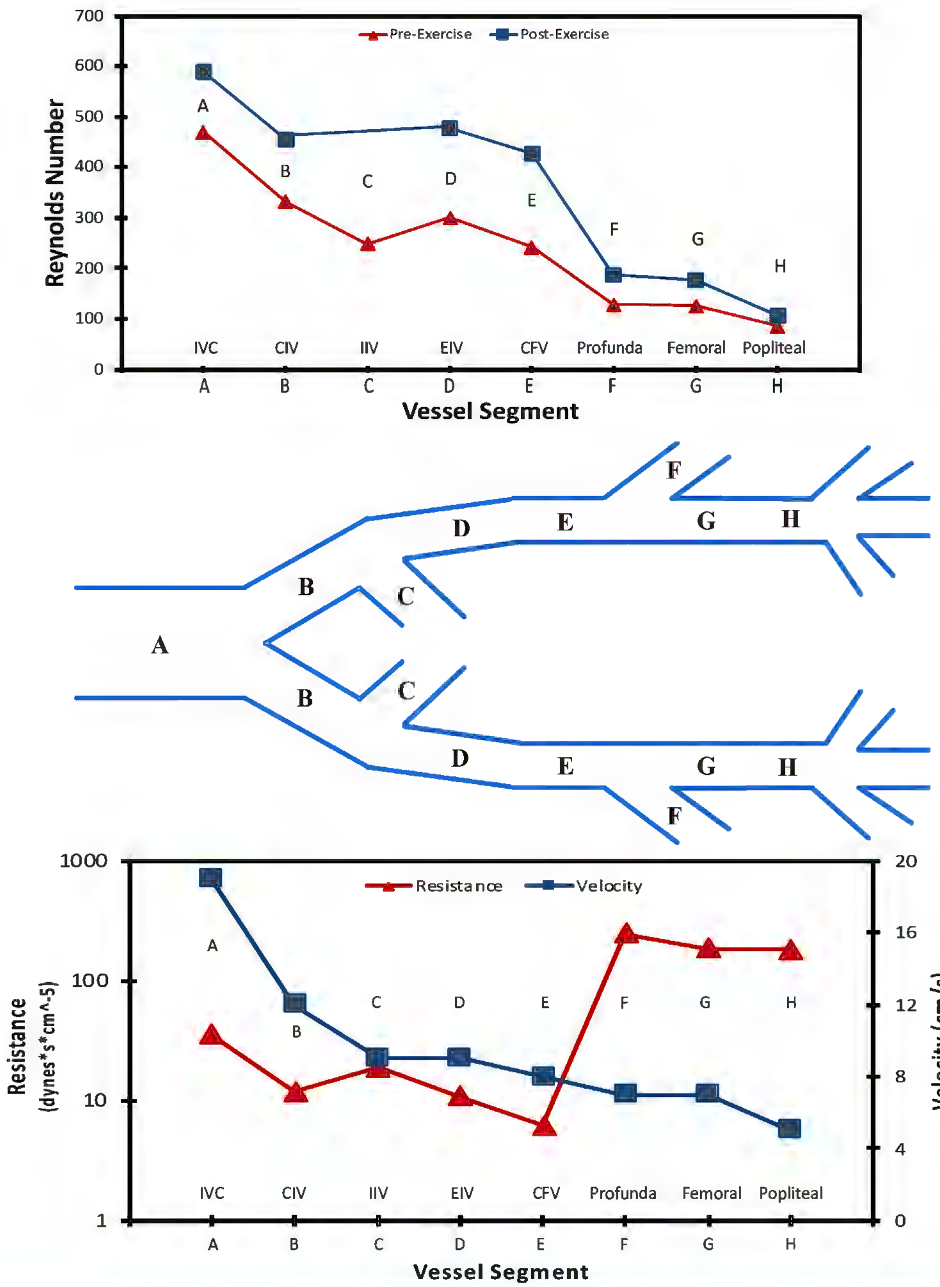
Supplementary Fig 2 (online only). Spearman correlation (*r*) for change in Reynolds number (R_e) before and after exercise for four veins (inferior vena cava [IVC], common iliac vein [CIV], external iliac vein [EIV], common femoral vein [CFV]) and weight (EIV: $r = 0.33$; $P =$ NS).



Supplementary Fig 3 (online only). Spearman correlation (*r*) for change in Reynolds number (R_e) before and after exercise for four veins (inferior vena cava [IVC], common iliac vein [CIV], external iliac vein [EIV], common femoral vein [CFV]) and height (IVC: $r = -0.15$; $P =$ NS).



Supplementary Fig 4 (online only). Spearman correlation (*r*) for change in Reynolds number (R_e) before and after exercise for four veins (inferior vena cava [IVC], common iliac vein [CIV], external iliac vein [EIV], common femoral vein [CFV]) and body mass index (BMI; EIV: $r = 0.37$; $P = .04$).



Supplementary Fig 5 (online only). Velocity, resistance, and Reynolds number (R_e) maps of venous system. Velocity and R_e will increase and resistance will decrease as one moves up the venous tree. *A,* Inferior vena cava (IVC); *B,* common iliac vein (CIV); *C,* internal iliac vein (IIV); *D,* external iliac vein (EIV); *E,* common femoral vein (CFV); *F,* profunda femoris vein; *G,* femoral vein; *H,* popliteal vein.