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Pulsed Doppler in Simulated Compartment Syndrome: A Pilot Study to Record Hemodynamic Compromise

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ABSTRACT

Background: Acute compartment syndrome occurs when the tissue pressure within a closed muscle compartment exceeds the perfusion pressure. We observed diastolic retrograde arterial flow (DRAF) in 2 patients in the arteries proximal to compartment syndromes in injured limbs. We hypothesized that DRAF may represent an early sign of compartment pressure increments.

Methods: We mimicked compartment syndrome by using a cuff to produce external compression of the forearm at increasing pressures. We correlated the applied pressure with brachial artery blood flow, velocities, and retrograde flow. We studied the brachial artery at baseline, at external compression of 40 mmHg applied to the forearm, at forearm compression equal to the patient's diastolic blood pressure (DBP), and at forearm compression equal to the patient's mean arterial pressure (MAP). Evaluations included Doppler velocities and DRAF percentage (%). Using a ROC analysis, we selected a DRAF (%) cutoff value for the identification of patients with an applied external pressure equal to or greater than their DBP and calculated its sensitivity and specificity.

Results: Compared with baseline, DRAF (%) was increased at 40 mmHg ($P<0.05$), at DBP ($P<0.05$), and at MAP ($P<0.05$). DRAF (%) was strongly correlated with applied external pressure ($r=0.92$, $r^2=0.85$). DRAF 40% presented a 100% sensitivity and a 93% specificity for identifying a compression equal to or greater than the patient's DBP.

Conclusion: DRAF (%) strongly correlates with the degree of external pressure applied to the brachial artery, suggesting it may represent a useful tool in the detection and evaluation of compartment syndrome.

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INTRODUCTION

Compartment syndrome is an emergency condition resulting from elevated pressure in a closed space that reduces blood flow and tissue perfusion.[1] Compartment syndrome may occur after limb trauma such as tibial shaft and forearm fractures, soft tissue injury without fracture, burns, and prolonged external compression.[2] Diagnosis is generally obtained by clinical examination,[3] but the examination can be supplemented by intracompartmental pressure measurement that is generally obtained by inserting a needle connected to an arterial line pressure transducer into the muscle compartment. Several marketed devices, as well as a noncommercial injection technique using a manometer,[4] are also available for taking pressure measurements. Symptoms and signs of compartment syndrome frequently include severe pain, peripheral neurological deficit, pallor, and pulselessness.[5-6] Because of the poor sensitivity of clinical examination,[7-9] in the presence of complex extremity trauma, the American College of Surgeons Committee on Trauma recommends immediate fasciotomy or frequent direct measurement of compartment pressures.[10]

We observed abnormal pulsed Doppler velocities in the artery proximal to the injured limb in 2 patients with compartment syndrome (Figures 1 and 2). Specifically, we found complete diastolic retrograde arterial flow (DRAF) and increased modified resistivity index (MRI). Impedance augmentation caused by the restriction of the large vessels at the fascia level as they enter and leave the compartment and/or by the local increased compression of intracompartment blood vessels in the compartment syndrome may produce an incremental retrograde flow. Similar parameters have been previously described when external compression was applied to the forearm

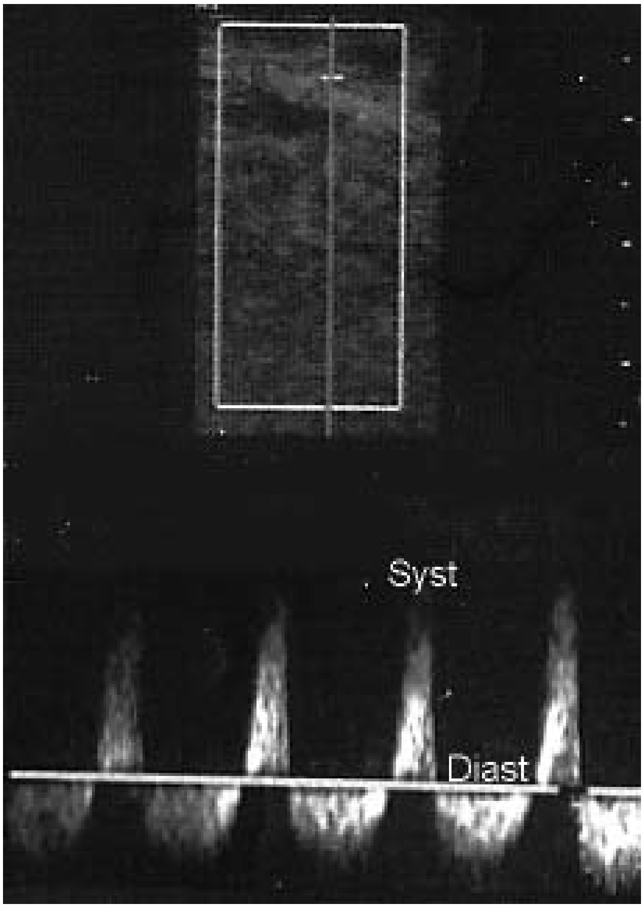

Figure 1. Complete diastolic retrograde arterial flow in the femoral artery of a 23-year-old male with compartment syndrome.

using a cuff.[11] However, the use of Doppler assessment to explore different types of compartment syndrome has yielded contradictory findings. No changes in arterial Doppler velocities were observed in chronic anterior tibial compartment syndrome[12] and chronic posterior compartment syndrome of the leg.[13] Doppler analysis of functional popliteal syndrome demonstrated a reduction of velocities and increased retrograde flow in the compromised patients during exercise.[14] Moreover, in studies of abdominal compartment syndrome, Doppler scan demonstrated increased renal resistivity index, retrograde flow, and reduced velocities.[15-19]

To our knowledge, no previous study has investigated the hemodynamics of arterial flow responses to acute forearm pressure increments. In this study, we investigated the hypothesis that the artery proximal to the injured limb would reflect the intracompartment pressure modifications. We hypothesized a strong correlation between pulsed Doppler velocities and acute pressure increments in the limb. Such a correlation could enable a new approach to the study of compartment syndromes using the noninvasive, economic, and widely available Doppler ultrasound equipment.

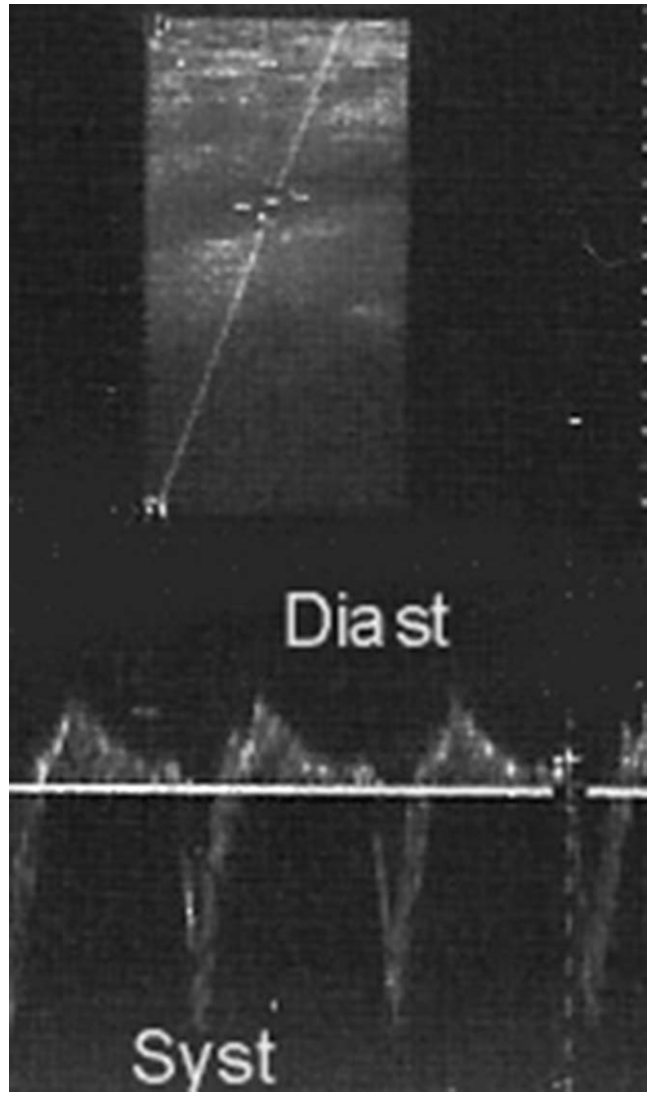

Figure 2. Complete diastolic retrograde arterial flow in the brachial artery of 72-year-old male with compartment syndrome.

METHODS

To test our hypothesis, we mimicked compartment syndrome by using a cuff to produce external compression of the forearm at increasing pressures and simultaneously evaluated the brachial artery Doppler parameters. Historically, a 20 mmHg pressure has been considered an indication for fasciotomy,[20] while others suggest that a <30 mmHg difference between intracompartmental pressure and diastolic blood pressure (DBP) is considered a more accurate indication for fasciotomy.[21] Therefore, we applied external pressure of 40 mmHg, pressure

Table 1. Demographics and Baseline Measurements of Study Participants (n=23)

Age, Years	Body Mass Index, kg/m^2	Systolic Blood Pressure, mmHg	Diastolic Blood Pressure, mmHg	Mean Arterial Pressure, mmHg	Brachial Artery Diameter, mm
31.4 ± 9.3	22.9 ± 3	119.3 ± 8.67	73.26 ± 9.07	88.6 ± 8.49	4.08 ± 0.6

Values are expressed as mean ± standard deviation.

equivalent to the patient's DBP, and pressure equal to the patient's organ perfusion pressure (mean arterial pressure [MAP]). We correlated the applied pressures with the brachial artery blood flow, velocities, and DRAF.

Subjects and Measurements

Twenty-three healthy volunteers (13 women) participated in this experimental study that was approved by the ethics committee of the Centro Médico Florida and that adhered to the Declaration of Helsinki. All subjects provided written consent. The study was performed in a quiet and temperature-controlled environment. Before each test, subjects were requested to fast for 6 hours, abstain from alcohol and caffeine for 18 hours, and avoid exercise for 24 hours.

Arterial blood pressure (systolic blood pressure [SBP]/DBP) was measured in a supine position in the patient's left arm before Doppler assessment, and the MAP was calculated [MAP = DBP + 1/3(SBP-DBP)] (Table 1). Baseline Doppler measurements and brachial artery diameters were obtained in the right arm while the patient was lying supine. Then, a cuff was placed around the patient's right forearm and inflated to 40 mmHg, to the DBP, and to the MAP of the patient with 1 minute for each stage and no rest between the stages. The ascending order of the cuff pressures was always 40 mmHg, DBP, and MAP for all patients.

Doppler Measurements

Doppler measurements were obtained at the 40 mmHg, DBP, and MAP external compression stages. The brachial artery was imaged approximately 5 cm proximal to the antecubital fossa in a transversal plane for diameter assessment and in a longitudinal plane for Doppler measurements using a commercially available ultrasound scanner (ATL HDI 3000, Royal Philips, The Netherlands) with an L12-5 5.0-12.0 MHz small parts, breast, musculoskeletal, and superficial vascular applications transducer. Quality control of equipment is routinely performed by the manufacturer's representative 3 times a year. Doppler velocity tracings were obtained with an angle of insonation inferior to 60 degrees. The wall filter was set at the lowest possible level (50 Hz). Because the intention was to measure brachial blood flow, sample volume was widely spaced to encompass the near and far walls of the artery, and simultaneous duplex (b-mode) Doppler technique was used to certify venous signals were not included in the tracing. Doppler scans were performed by a senior radiologist with more than 20 years of experience with this technique.

Calculations made with the ultrasound equipment's built-in software included peak systolic velocity (PSV), minimum diastolic velocity (MDV), pulsatility index (PI), and MRI for triphasic flow (this calculation considers minimum diastolic velocity instead of end diastolic velocity: MRI=PSV-MDV/PSV). Mean flow velocity was calculated as PSV-MDV/PI.

DRAF duration (milliseconds [ms]) was measured in one heartbeat. DRAF (%) was calculated as DRAF duration/total heartbeat duration × 100. A heartbeat in which both systolic and diastolic flow move forward all the time would have a DRAF (%) of 0 (zero), while a heartbeat in which the blood flow is unable to progress at any moment would have a DRAF (%) of 100.

Brachial blood flow (cm^3/s) was calculated as mean flow velocity × cross-sectional area, and the blood flow reduction percentage compared with baseline was established at 40 mmHg, DBP, and MAP for each patient.

Statistics

Statistical analysis was performed using SPSS for Windows, version 17.0 (IBM, Armonk, NY). Continuous variables were expressed as mean ± 1 standard deviation. Because of the normal distribution of the results, a one-way repeated measures ANOVA was used to compare the changes within subjects throughout the study, and $P<0.05$ was considered significant. When a significant change was found, the Bonferroni post hoc procedure was used for pairwise comparisons. Linear regression was used to examine the correlation between DRAF (%) and the applied external pressure and between the DRAF (%) and blood flow reduction. In addition, receiver operating characteristic (ROC) curve analysis was used to assess the ability of the DRAF (%) value to discriminate patients with an applied external pressure equal to or greater than their DBP and to select an optimal cutoff value. The 4 tested cutoff values in the ROC analysis were DRAF (%) $\geq$30, $\geq$40, $\geq$50, and $\geq$60. Sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) for the identification of patients with an applied external pressure equal to or greater than their DBP were calculated for the optimal DRAF (%) cutoff value obtained from the ROC analysis.

RESULTS

A summary of the Doppler velocity results is presented in Table 2. External pressure compression resulted in a significant increase of DRAF (ms), DRAF (%), PI, and MRI. At baseline, only 2 patients presented complete DRAF (%), while at MAP compression, all the patients presented complete retrograde flow after systolic deceleration (Figure 3).

Compared with baseline, DRAF (%) increased at 40 mmHg compression (0.54 $\pm$ 2.12 vs 23.13 $\pm$ 15.45, $P<0.05$), at DBP compression (0.54 $\pm$ 2.12 vs 59.54 $\pm$ 9.97, $P<0.05$), and at MAP compression (0.54 $\pm$ 2.12 vs 79.75 $\pm$ 5.72, $P<0.05$). Likewise, DRAF (%) increased with the ascending external compression from 40 mmHg to DBP ($P<0.05$) and from DBP to MAP ($P<0.05$).

Negative MDV increased with the graded external compression increments compared with baseline (3.67 $\pm$ 3.06 vs –4.49 $\pm$ 2.97, $P<0.05$; vs –8.88 $\pm$ 4.39, $P<0.05$; and vs –13.24 $\pm$ 6.37, $P<0.05$ for the 40 mmHg, DBP, and MAP compressions, respectively). Negative MDV also significantly increased with ascending external compression from 40 mmHg to DBP ($P<0.05$) and from DBP to MAP ($P<0.05$).

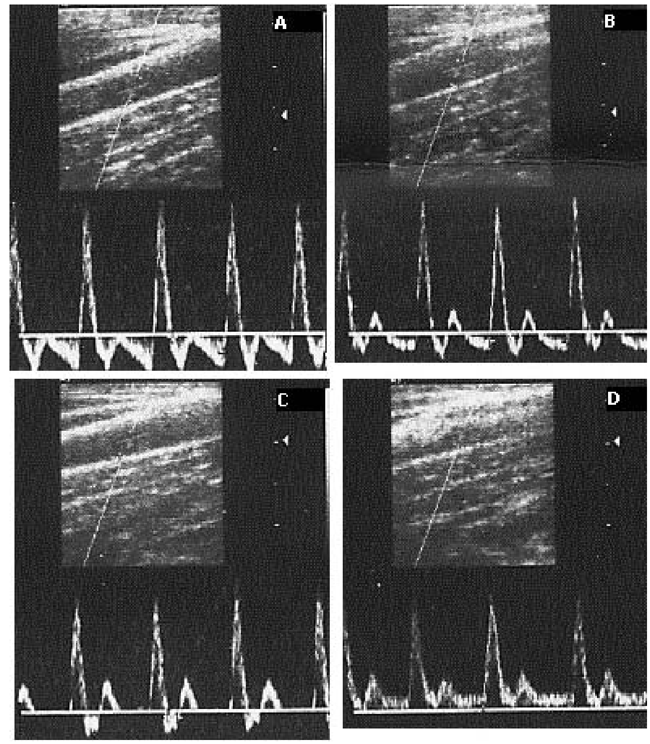

Figure 3. Pulsed Doppler images obtained from the brachial artery of a normal subject at baseline and as ascending pressure is applied to the forearm: A—external compression equal to diastolic blood pressure; B—external compression equal to mean arterial pressure; C—baseline; and D—external compression of 40 mmHg.

PSV was similar during the 4 stages of the experimental study.

Figure 4A shows that DRAF (%) was positively correlated with the applied external pressure with a

Table 2. Summary of Doppler Velocities, Blood Flow, and Retrograde Flow at Increasing Pressures (n=23)

Variable	Baseline	40 mmHg	Diastolic Blood Pressure	Mean Arterial Pressure
Peak Systolic Velocity, cm/s	50.09 $\pm$ 25.19	50.9 $\pm$ 23.96	50.63 $\pm$ 21.97	51.61 $\pm$ 22.14
Minimum Diastolic Velocity, cm/s	3.67 $\pm$ 3.06	−4.49 $\pm$ 2.97[a]	−8.88 $\pm$ 4.39[a,b]	−13.24 $\pm$ 6.37[a,b,c]
Modified Resistivity Index	0.93 $\pm$ 0.02	1.07 $\pm$ 0.06[a]	1.16 $\pm$ 0.05[a,b]	1.22 $\pm$ 0.05[a,b,c]
Pulsatility Index	4.84 $\pm$ 1.1	10.99 $\pm$ 4.47[a]	25.66 $\pm$ 10.83[a,b]	41.60 $\pm$ 14.57[a,b,c]
Mean Velocity, cm/s	10.14 $\pm$ 6.4	5.61 $\pm$ 3.32[a]	2.63 $\pm$ 1.40[a,b]	1.68 $\pm$ 0.71[a,b,c]
Blood Flow, cm^3/min	81.83 $\pm$ 58.2	45.82 $\pm$ 30.21[a]	21.25 $\pm$ 11.81[a,b]	13.03 $\pm$ 4.87[a,b,c]
Blood Flow Reduction, %	N/A	42.06 $\pm$ 17.22	68.29 $\pm$ 12.86[b]	80.36 $\pm$ 10.26[b,c]
Diastolic Retrograde Arterial Flow, ms	5.2 $\pm$ 21.07	204.7 $\pm$ 143.9[a]	534.3 $\pm$ 110.4[a,b]	716.5 $\pm$ 85.31[a,b,c]
Diastolic Retrograde Arterial Flow,[d] %	0.54 $\pm$ 2.12	23.13 $\pm$ 15.45[a]	59.54 $\pm$ 9.97[a,b]	79.75 $\pm$ 5.72[a,b,c]

Values are expressed as mean $\pm$ standard deviation.
N/A, not applicable.
[a]$P<0.05$ compared with baseline.
[b]$P<0.05$ compared with 40 mmHg.
[c]$P<0.05$ compared with diastolic blood pressure.
[d]Diastolic retrograde arterial flow percentage [DRAF (%)]=DRAF duration in milliseconds (ms)/total heartbeat duration $\times$ 100.

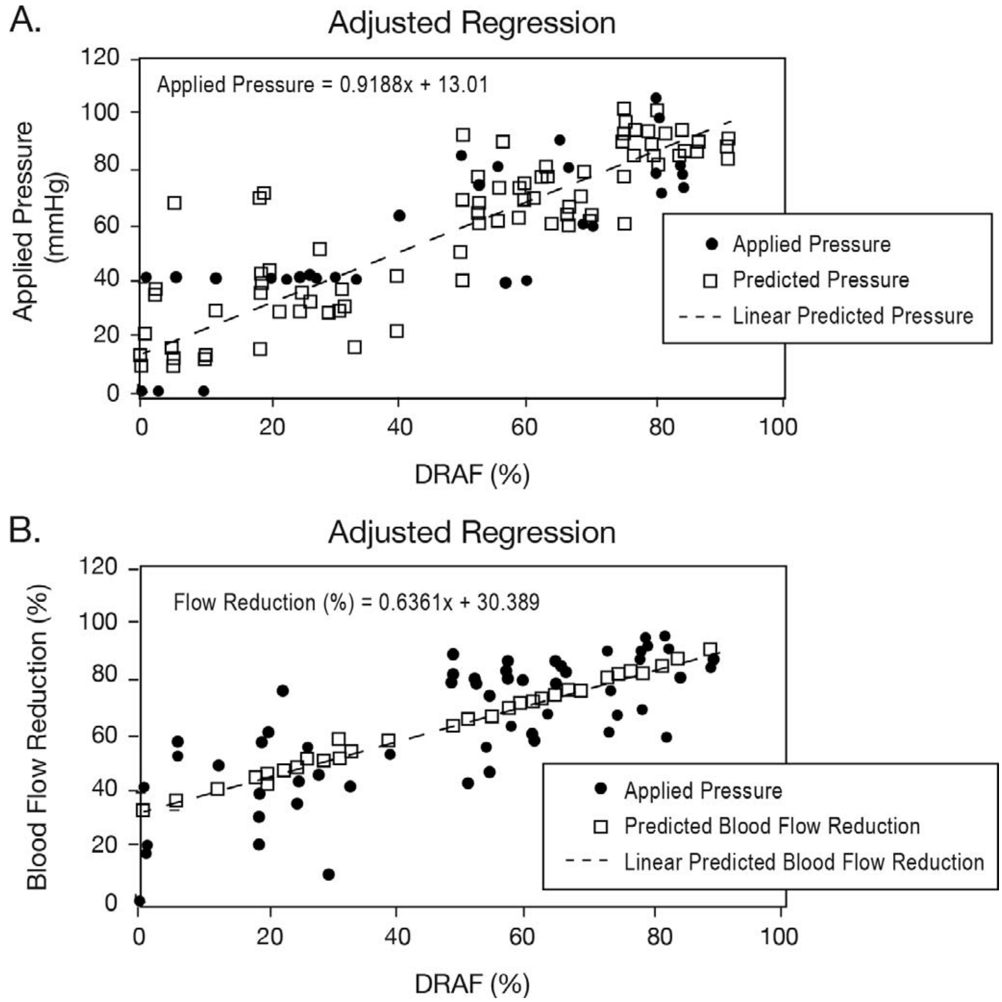

Figure 4. A. Adjusted linear regression for the correlation of diastolic retrograde arterial flow percentage [DRAF(%)] and external applied pressure. B. Adjusted linear regression for the correlation of DRAF(%) and the blood flow reduction percentage compared with baseline.

high correlation coefficient ($r=0.92$, $r^2=0.85$, $P<0.0001$). DRAF (%) was also positively correlated with blood flow reduction (%) from baseline (Figure 4B; $r=0.77$, $r^2=0.60$, $P<0.0001$). MRI was positively correlated with the applied external pressure ($r= 0.89$, $r^2=0.80$, $P<0.0001$) and with blood flow reduction (%) ($r=0.61$, $r^2=0.36$, $P<0.0001$).

ROC analysis for selecting the optimal cutoff value to identify patients with an external compression equal to or greater than DBP (Figure 5) showed that the cutoff values of DRAF 40% and DRAF 50% presented identical areas under the curve (0.967 ± 0.21). Therefore, we studied the sensitivity, specificity, PPV, and NPV for both values (Table 3). DRAF 40% presented a 100% sensitivity, a 93% specificity, a PPV of 94%, and an NPV of 100%. DRAF 50% presented a 98% sensitivity, a 96% specificity, a PPV of 96%, and an NPV of 98%.

DISCUSSION

Compartment syndrome compromises venous and lymphatic drainage of the injured area as well as arterial perfusion. This reinforcing vicious circle leads finally to tissue ischemia and irreversible damage. Because of the diastolic lower perfusion gradient, we have hypothesized that limited drainage from a compartment and increased impedance to antegrade flow at the muscular fascia may rapidly produce changes in the proximal diastolic arterial flow. These changes may be detected and quantified using Doppler—a new approach to this clinical scenario.

Our results showed that brachial DRAF (%) and MRI are markedly increased by pressure increments applied to the forearm, while mean velocity and blood flow are reduced. Finally, cutoff values of DRAF 40% and DRAF 50% suggest that the applied external compression is equal to or greater than the patient's

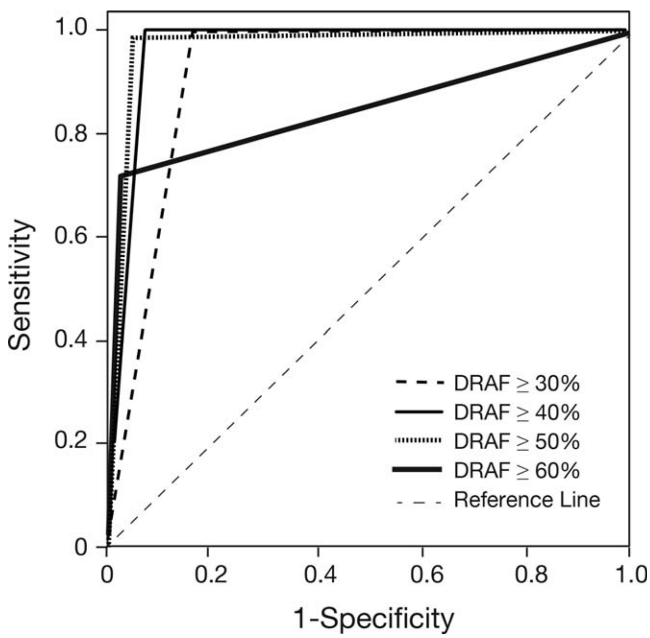

Figure 5. Receiver operating characteristic analysis for the diastolic retrograde arterial flow percentage [DRAF (%)] cutoff values for identifying an applied external pressure greater than or equal to the patient's diastolic blood pressure. Diagonal segments are produced by ties.

DBP with a sensitivity and specificity of 98%-100% and 93%-96%, respectively.

Our study was not designed to calculate the actual intracompartment pressure but rather to describe the patients' limb hemodynamic situations. In a clinical scenario, a value of DRAF 50% would allow the radiologist to infer that the brachial artery hemodynamic situation is similar to the one observed when the forearm is acutely exposed to an external compression equal to or greater than the patient's DBP but not to infer the actual compartment pressure. Using the formula presented in Figure 4A, the radiologist could calculate a predicted value of the external compression necessary to produce such DRAF (%). Moreover, regarding the limb blood flow, although we observed a strong correlation between blood flow reduction and DRAF (%) values, a useful clinical approach might be to explore the contralateral limb artery and to infer blood flow reduction as compared with the contralateral limb. We believe that DRAF >40% may represent a useful description of the injured limb hemodynamics that would enable the clinician to evaluate the patient's evolution through time (eg, hourly evaluation in the emergency department) and to classify patients in further investigations. Furthermore, although we tested our hypothesis only in the forearm, we believe compartment syndrome in any extremity could be evaluated using this technique.

Table 3. Results of the 23 Patients During the 4 Stages of the Study

	Compression >DBP	Compression <DBP
DRAF <40%	0	43
DRAF >40%	46	3
DRAF <50%	1	44
DRAF >50%	45	2

Note: Patients were studied in the 4 stages resulting in 92 measurements. Sensitivity, specificity, positive predictive value, and negative predictive value were obtained from these values.

Study Limitations

Because we recruited volunteers without randomization and did not calculate a necessary sample size, our research design does not allow for any generalizations beyond describing this small cohort of volunteers. Moreover, when applying external pressure using a cuff, the forearm represents a single compartment. Although this situation may be observed in major burns or traumas involving sustained external compression, compartment syndromes in the limbs can be also confined to only 1 of the intrafascial compartments.[22] Likewise, multiple branches of the arterial tree contribute to limb perfusion, and the compression cuff possibly could constrict the brachial artery being investigated while other vessels are not interrogated. Another limitation of our study is that elderly patients, limb elevation, or active muscle contraction present significant spontaneous DRAF that could be misinterpreted or modify the correlation between the external applied pressure and the DRAF.[23-24] Despite this fact, complementary contralateral limb Doppler examination can easily demonstrate if the observed DRAF is part of a generalized flow pattern or if it is the result of a local alteration. In addition, muscle relaxation and the correct positioning of the limb (avoiding limb elevation) can be easily taken into consideration when performing the Doppler scan.

CONCLUSION

Increased pressure in a compartment produces DRAF in the proximal artery that can be detected and quantified using the Doppler technique. DRAF strongly correlates with the degree of pressure applied to the limb, suggesting that DRAF analysis may be a useful tool for detecting and evaluating the hemodynamics in a compartment syndrome. Given the promising results from this pilot study, further investigation, such as a case-controlled study in a real clinical scenario, may determine the clinical value of this technique.

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