◆ CLINICAL INVESTIGATION ◆

Angiography Underestimates Peripheral Atherosclerosis: Lumenography Revisited

Vikram S. Kashyap, MD; Mircea L. Pavkov, MD; Paul D. Bishop, MSEE; Sean P. Nassoïy, BS; Matthew J. Eagleton, MD; Daniel G. Clair, MD; and Kenneth Ouriel, MD

Department of Vascular Surgery, The Cleveland Clinic, Cleveland, Ohio, USA.

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Purpose: To compare angiograms, considered the gold standard for diagnostic imaging of peripheral arterial disease (PAD), to the corresponding histological sections of popliteal and tibial vessels obtained after amputation to determine if angiography fails to define atheroma burden in “normal appearing” arteries in patients with PAD.

Methods: Between 2004 and 2006, 69 patients underwent amputation of a lower extremity for severe tissue loss, gangrene, or pedal sepsis precluding limb salvage. Popliteal and tibial vessels were harvested, perfusion-fixed, and analyzed histologically. Thirty-four of these patients had pre-amputation angiography during attempted salvage procedures. Angiograms with patent or minimally diseased vessel segments (n=19) were assessed for stenoses, diameter, and calcification by 3 vascular surgeons (n=72 evaluations). These results were compared to corresponding cross-sectional histological slides (n=66) in a blinded manner.

Results: Angiograms performed prior to above-knee (n=9) or below-knee (n=10) amputation revealed 24 stenoses with a mean ($\pm$ SD) diameter-reducing stenosis of $19.5\% \pm 15.2\%$. Corresponding histological cross sections revealed greater linear stenoses measured via boundaries of the internal elastic lamina (IEL stenosis, $28.9\% \pm 20.2\%$, $p=0.003$ versus angiography) or via boundaries of the external elastic membrane (vessel stenosis, $43.1\% \pm 15.2\%$, $p<0.0001$). Stenosis calculated by area methods (IEL area) were greater and measured $39.2\% \pm 24.2\%$ ($p<0.0001$) and $60.9\% \pm 15.2\%$ (vessel area, $p<0.0001$). Popliteal arteries had greater discrepancy in stenosis measurement than tibial arteries ($18.5\% \pm 14.6\%$ versus $34.9\% \pm 21.0\%$, $p=0.0005$). However, evaluations of tibial arteries for concentricity of plaque (44% versus 69%, $p=0.08$) and calcification grade (1.6 versus 2.2, $p=0.002$) by angiography were discordant with histological analyses. Measurement of arterial diameter by histology for popliteal arteries (6.2 ± 0.9 mm) and tibial arteries (3.1 ± 0.7 mm) was greater than angiographic diameter determination ($p<0.001$).

Conclusion: Angiography provides information on luminal characteristics of peripheral arteries but severely underestimates the extent of atherosclerosis in patients with PAD even in “normal appearing” vessels.

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Key words: peripheral artery disease, stenosis, atheroma, popliteal artery, tibial artery, histology, angiography

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The introduction of angiography^{1–3} revolutionized the diagnosis and management of arterial disease in multiple vascular beds.

Despite incorporation of this technique into common medical practice, the limitations of this modality have become appreciated over

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Address for correspondence and reprints: Vikram S. Kashyap, MD, The Cleveland Clinic, Department of Vascular Surgery, S40, 9500 Euclid Avenue, Cleveland, OH 44195 USA. Fax: 1-216-444-9324; E-mail: kashyav@ccf.org

time. The necessity of arterial access with possible arterial damage (catheter-related embolism, thrombosis, or dissection) and contrast-induced systemic effects, including renal failure, have all been accepted as risks and limitations of angiography. A lesser appreciated limitation, however, is that angiography provides information about only the lumen and lumen-border interface. Thus, information about arterial plaque burden and morphology are based on inference from the interpretation of luminal and border characteristics.

Experienced vascular specialists appreciate that angiography underestimates the degree of atherosclerosis in diseased, stenotic arteries. However, angiography is used routinely to select the location of distal anastomoses for arterial reconstruction and the adequacy of endovascular therapies based on luminal information and characteristics. Our hypothesis was that contrast angiography does not reflect the burden of atherosclerotic plaque in "normal appearing" arteries in patients with peripheral artery disease (PAD). The objective of this study was to compare angiographic images of "normal appearing" lower extremity arteries to corresponding histological slides of the same lower extremity artery obtained after amputation.

METHODS

Patient Population

Between 2004 and 2006, ~900 patients per year underwent endovascular therapy or open surgical reconstruction at our institution for symptoms related to PAD. During this time period, 69 (2.5%) individuals underwent lower extremity amputation. Despite an aggressive departmental approach to limb salvage, these patients required below-knee or above-knee amputation for ongoing critical ischemia, overwhelming tissue loss, ascending gangrene, or pedal sepsis precluding limb salvage. Of these 69 patients, 34 had an angiogram for evaluation within 180 days (mean 53 days) prior to amputation. Patients with a patent, minimally diseased, or "normal appearing" segment of lower extremity artery on angiography formed the basis for this

study (n=17 patients, 19 segments). Two patients had both patent "normal appearing" popliteal and tibial vessels for evaluation. Of note, angiograms showing any evidence of greater than minimal atherosclerosis (>30% stenosis) in the segments of interest were excluded from analyses. Similarly, clinical evidence of vasculitis, fibromuscular dysplasia, or other non-atherosclerotic arterial disease led to exclusion.

Analysis and Grading of Angiograms

Angiography was performed in dedicated endovascular suites using a fixed digital angiographic system (AngioSTAR; Siemens AG, Munich, Germany). The original angiographic images were captured and stored electronically (MagicView; Siemens AG). Selected images (by MLP) of patent and "normal appearing" popliteal and tibial vessels with no apparent stenosis >30% were evaluated separately by 3 experienced vascular surgeons blinded to any results of the histological analyses. Both digital subtraction and the corresponding non-subtracted angiographic images were reviewed without magnification. Angiographic runs of the arterial segment to be evaluated (popliteal and/or tibial) were reviewed with multiple projections if available, but proximal inflow and pedal outflow images were not shown to minimize any bias. Evaluation of the angiograms included presence and location of stenoses, diameter-reducing percent stenosis if present, proximal and distal vessel diameter, concentricity of any stenosis, and ordinal grading of calcification of any stenosis. Stenosis percentage was determined by using the proximal adjacent "normal" artery for reference (1-stenosis diameter/proximal diameter). Concentricity was graded dichotomously as either a concentric or eccentric plaque. Grading of calcification was on a 0 to 3 scale (0=none, 1=minimal calcification, 2=moderate calcification, and 3=severe).⁴ Diameters were recorded in millimeters.

Human Arterial Analyses

Arteries from lower extremity amputations were harvested as part of an National Insti-

tutes of Health-sponsored study entitled "Clinical implications of peripheral plaque morphology" (RO1HL075721). These studies were approved by the Cleveland Clinic Institutional Review Board (#6723).

Following amputation, arteries were harvested within a 24-hour period and underwent perfusion fixation. Patent anterior tibial, posterior tibial, and peroneal arteries were harvested from below-knee amputations. Additionally, patent popliteal arteries were harvested from above-knee amputations. Vessels were perfusion fixed at 100 mmHg using HistoChoice (Amresco, Solon, OH, USA) tissue fixative for 6 to 8 hours at room temperature. Desired regions on the vessel were designated by a suture mark. Specimens were sectioned and sent to histology for processing (Lerner Research Institute, Core Lab, Cleveland, OH, USA).

Electronic images of all histological slides were stored and analyzed using ImageJ software (<http://rsb.info.nih.gov/ij/>) with repeat measures (n=3) of all lengths and borders. Measurements for stenosis were done using both linear and area measurements (Fig. 1). The "internal elastic lamina (IEL) stenosis" is the closest histological correlative to an angiographic stenosis, since it represents the minimal diameter produced by atheroma divided by the diameter between internal elastic laminae (Fig. 1A). The "vessel stenosis" is another linear stenosis measurement using the vessel wall distance as the denominator (external elastic membrane to external elastic membrane). Stenoses were also calculated by the area burden that they occupied in the vessel, both in relationship to the true vessel diameter ("vessel area stenosis"), as well as the plaque compared to the internal elastic lamina ("IEL area stenosis," Fig. 1B). Similar to the angiographic grading, concentricity was graded dichotomously as either a concentric or eccentric plaque. Calcium content of plaque was graded on a modified ordinal scale corresponding to angiographic scoring: 0=none, 1=minimal, 2=patchy, and 3=extensive and/or circumferential calcification. Matching of histological slices with angiographic imaging was performed using length measurements and branch and collateral orifices as landmarks.

Figure 1 ♦ Linear (A) and area (B) stenosis measurements. Vessel area stenosis is also called plaque or atheroma burden.

Statistical Analysis

Categorical measures were analyzed with chi-square tests; for continuous variables, 2-sided *t* tests were performed. Variances are given as the mean ± standard deviation;

$p < 0.05$ was considered significant. Interobserver agreement for evaluation of concentricity was assessed with the kappa statistic; for degree of stenosis and calcification, the Kendall coefficient of agreement was used with 1 being maximum agreement.

RESULTS

Nineteen angiograms of "normal appearing" or "minimally diseased" patent vessels had 24 stenoses in the lower extremity arteries identified. Of the 72 evaluations performed, all arteries were characterized as $< 30\%$ stenosed except for 9 areas between 30% and 50% . The mean stenosis percentage for all lesions identified was $19.5\% \pm 15.2\%$.

We had a very high rate of interobserver agreement of the cases reviewed. For the presence of a stenosis, the number of positive answers was very high (68), with only 4 judgments not correlating. Thus, all 3 observers agreed in 83.3% of cases. For the degree of stenosis, the u coefficient of agreement of Kendall was 0.6612, considered substantial, good agreement. The Kendall coefficient was 0.5397 (good agreement) for the proximal diameter and 0.5402 (good agreement) for the distal diameter. After pairing the observers, the kappa value for interobserver variability for concentricity evaluations was 0.7314 (substantial agreement). Finally, the calcification scoring gave a Kendall coefficient of 0.3985 (moderate agreement).

Histology evaluation of the same arteries was compared to angiographic results (Fig. 2). On cross-sectional slides, stenoses were calculated by both linear and area methods. Accuracy of measurements was high, with a 0.0887-mm mean standard deviation for linear pathology measurements. By all parameters, angiographic scoring of atherosclerotic burden underestimated the presence and amount of atherosclerosis in patients with PAD and "normal appearing arteries" on arteriography (Table 1). The mean IEL stenosis was $28.9\% \pm 20.2\%$ compared to $19.5\% \pm 15.2\%$ by angiographic scoring ($p = 0.003$). Also, the mean vessel stenosis was $43.1\% \pm 15.2\%$ ($p < 0.0001$). As expected, measurement of stenoses by area led to increasingly discrepant results compared to

Figure 2 ♦ A comparison of angiography to histology of the popliteal artery. (A) Digital subtraction angiography reveals a fairly normal appearing popliteal artery without evidence of a high-grade stenosis or significant atheroma burden. The lines indicate the level of the popliteal artery where serial histological slides were obtained (including C). (B) Non-subtracted angiography of the foot revealing significant pedal occlusive disease. Pedal sepsis led to amputation 3 days later. (C) Movat trichrome histology of the popliteal artery revealing significant atheroma burden and circumferential calcification.

angiography. IEL area stenosis measured $39.2\% \pm 24.2\%$ ($p < 0.0001$ compared to angiographic scoring), while vessel area stenosis measured $60.9\% \pm 15.2\%$ ($p < 0.0001$).

Subset evaluation of popliteal versus tibial arteries indicated greater discrepancy for popliteal evaluation than for tibial artery

TABLE 1
Comparison of Angiographic Versus Histological Analyses of Lower Extremity Arteries

	Angiographic Analysis	Histological Analysis	p
Stenosis measurement, %	19.5±15.2		
IEL stenosis, %		28.9±20.2	0.003
Vessel stenosis, %		43.1±15.2	<0.0001
IEL area stenosis, %		39.2±24.2	<0.0001
Vessel area stenosis, %		60.9±15.2	<0.0001
Concentric plaque	23/59 (39%)	35/65 (54%)	0.11
Calcification scoring	1.7±0.9	2.1±0.8	0.003

Continuous data are presented as means±standard deviation.
IEL: internal elastic lamina.

evaluation by angiography versus histological analysis (Table 2). In the popliteal location, reviewers identified stenoses with a mean stenosis of 18.5%±14.6% (range 0%–50%). Histological analysis revealed a mean IEL stenosis nearly double the angiographic scoring: 34.9%±21.0% (p=0.0005). The linear stenosis measured using the vessel wall was 47.4%±14.2% (p<0.0001). Also, both IEL (46.5%±25.9%) and vessel (66.0%±13.7%) area stenoses revealed significant plaque

burden compared to angiographic scoring (p<0.0001). Evaluation of tibial arteries showed closer correlation between angiographic stenosis determination (20.4%±15.8%) and IEL stenosis (22.3%±17.1%; p=NS) measurement. However, vessel stenoses (38.3%±14.9%, p<0.0001) and area measurements indicated significantly increased atheroma burden (IEL area stenosis 31.4%±19.8%, p=0.01, versus vessel area stenosis 55.5%±15.0%, p<0.0001).

TABLE 2
Comparison of Popliteal and Tibial Arteries by Angiography and Histology

	Angiographic Analysis	Histological Analysis	p
Popliteal arteries			
Stenosis measurement, %	18.5±14.6		
IEL stenosis, %		34.9±21.0	0.0005
Vessel stenosis, %		47.4±14.2	<0.0001
IEL area stenosis, %		46.5±25.9	<0.0001
Vessel area stenosis, %		66.0±13.7	<0.0001
Concentric plaque	9/27 (33%)	13/33 (39%)	NS
Calcification scoring	2.0±0.8	1.8±1.1	NS
Maximum diameter, mm	3.7±0.8		
Luminal diameter, mm		3.8±1.1	NS
Arterial wall diameter, mm		6.2±0.9	<0.0001
Tibial arteries			
Stenosis measurement, %	20.4±15.8		
IEL stenosis, %		22.3±17.1	NS
Vessel stenosis, %		38.3±14.9	<0.0001
IEL area stenosis, %		31.4±19.8	0.01
Vessel area stenosis, %		55.5±15.0	<0.0001
Concentric plaque	14/32 (44%)	22/32 (69%)	0.08
Calcification scoring	1.6±0.8	2.2±0.7	0.002
Maximum diameter, mm	2.5±0.5		
Luminal diameter, mm		2.1±0.6	0.004
Arterial wall diameter, mm		3.1±0.7	0.0004

Continuous data are presented as means±standard deviation.
IEL: internal elastic lamina, NS: not significant.

Evaluation of angiographic images for the concentricity and calcification of atherosclerotic disease was discordant compared to histology. On angiographic analyses, 23 (39%) of 59 plaque evaluations were concentric. However, on histological analysis of 65 slides from the same vessels, concentric plaque was present in 35 (54%) specimens ($p=0.11$, Fisher exact test). Similarly, angiographic evaluation underestimated the extent of arterial calcification in these selected lower extremity vessels. The mean score for angiographic evaluation was 1.7 ± 0.9 versus 2.1 ± 0.8 ($p=0.003$, t test) for histology. Angiographic evaluation led to 15% of scores being 0 compared to 0% on histology; 15% had angiographic scores of 3 versus 34% by histology.

When popliteal arteries were analyzed separately from tibial arteries, concentricity and calcification of atherosclerotic disease were more discordant for tibial arteries (Fig. 3). For popliteal arteries, concentricity of any stenosis was 33% on angiography versus 39% on histological analysis ($p=NS$, Fisher exact test). However, for tibial arteries, concentricity of any stenosis was 44% on angiography versus 69% on histology ($p=0.08$, Fisher exact test). Similarly, calcification scoring of popliteal arteries correlated more closely than for tibial arteries. The mean angiographic score of popliteal arteries was 2.0 ± 0.8 versus 1.8 ± 1.1 from histological analyses for calcification ($p=NS$, t test). For tibial arteries, the mean angiographic score was 1.6 ± 0.8 , while histological scoring was 2.2 ± 0.7 ($p=0.002$, t test).

Lastly, vessel size was compared between angiography versus histology as the true diameters of the vessels. The mean diameter of popliteal arteries was estimated by review of angiograms as 3.7 ± 0.8 mm, which was analogous to the 3.8 ± 1.1 -mm maximum luminal diameter by histology. However, the true arterial diameter measured from the external elastic membrane border of popliteal vessels was 6.2 ± 0.9 mm ($p<0.001$, t test). For tibial arteries, the angiographic diameter was estimated to be 2.5 ± 0.5 mm. Both luminal diameters (2.1 ± 0.6 mm, $p=0.004$) and arterial diameters (3.1 ± 0.7 mm, $p<0.001$) were statistically different by histological analyses.

Figure 3 ♦ Variability of atheroma burden in tibial arteries. Histology of a patent posterior tibial artery (A) and anterior tibial artery (B) in the same patient.

DISCUSSION

Contrast catheter angiography remains the “gold standard” in the evaluation of patients with PAD. It plays a critical role in identifying areas of atherosclerotic disease and occlusion. Furthermore, it allows subjective evaluation of blood flow, aids in planning operative revascularization, and is obligatory for endovascular interventions. Despite its critical role, angiography gives us a 2-dimensional (2D) cast of the artery and thus has significant inherent limitations, such as the fluoroscopic planar angle, luminal structure, vessel tortu-

osity, overlying structures, and overlap of other vessels, which all confound accurate depiction of the true 3-dimensional (3D) arterial anatomy.

Since Sones and Shirey¹ described coronary angiography nearly 50 years ago, improvements have been rigorously studied and discrepancies between coronary angiograms and actual arterial morphology well described. In an early study, coronary specimens were obtained at 10 necropsies and compared to premortem coronary angiograms.⁵ In 33% of 134 coronary segments evaluated, arteriography led to a false-negative diagnosis of coronary artery disease (CAD). Thus, a large fraction of coronary arteriograms were interpreted as having <50% occlusive disease, while in actuality there was >50% atherosclerotic narrowing. Isner and colleagues⁶ confirmed this finding for the left main coronary artery, a notoriously difficult vessel to completely study by angiography. Coronary arteries obtained at necropsy of 28 patients were compared to premortem coronary angiograms. Consistent with our findings, a large percentage (39%) of the angiograms were underestimates of the burden of disease. Surprisingly, 25% of the angiogram evaluations were overestimates of occlusive disease in the left main coronary artery. The authors concluded that coronary angiography could be prone to significant error due to the limitations of angiographic projections and the atherosclerotic process.

The limitations of coronary angiography have become appreciated.⁷ Both the accuracy and reproducibility of plaque determination have been questioned where any single angle giving a 2D view of luminal contrast flow can misrepresent the extent, nature, and severity of atheroma burden. Due to the limitations of coronary angiography, other modalities have been evaluated for coronary assessment. Magnetic resonance imaging (MRI) and computed tomography (CT) allow noninvasive interrogation of the coronary vessels, and these techniques have been applied to peripheral vessels.^{8,9} Importantly, intravascular ultrasound (IVUS) has been utilized increasingly in assessment of coronary plaque volume, plaque morphology, and effects of treatment. Use of this sensitive and accurate

technology has allowed demonstration of coronary plaque stabilization and inhibition of progression of atherosclerosis with potent lipid-lowering therapy.^{10,11} Furthermore, newer generation angiographic equipment with rotational angiography and 3D reconstruction may aid in the imaging of peripheral arteries.¹²

The pathophysiology of peripheral atherosclerosis is based largely on coronary observations. Much of our understanding of atheroma burden and plaque progression is extrapolated from coronary studies, and direct evidence in peripheral atherosclerosis remains scant. Current data suggest that despite similar risk factors, atheroma progression and pathophysiology in these arterial beds may be distinct.^{13,14} The extent of atherosclerosis in peripheral arteries, prevalence of arterial occlusions rather than stenoses, and the resilience of the leg muscle and foot versus myocardium are all features differentiating PAD from CAD and worthy of further study.

Similarly, the limitations of angiography have been characterized for coronary circulation but have not been examined in peripheral atherosclerosis. In this study, we compared angiographic analyses to the pathology of the same arteries examined by histology after amputation in situations precluding limb salvage. It must be emphasized that our group has an aggressive posture for limb salvage, and the 69 patients undergoing amputation represented only ~2.5% of the total cases undergoing treatment for PAD during a 3-year interval. We observed that high-quality digital subtraction angiography severely underestimates the burden of atherosclerotic disease in peripheral arteries. Despite the “normal” or “minimally diseased” appearance of popliteal/tibial arteries on angiography, patients with PAD have disseminated atheroma burden throughout the leg arteries.

Limitations

In this study, we chose to compare “normal appearing” arteries on angiograms to their histological correlate. Additional studies evaluating stenotic (>30%) areas of lower ex-

tremity arteries using both angiography and IVUS are currently underway. We expect to find that angiography underestimates the severity of stenoses in overtly diseased vessels as well. Despite the use of landmarks, the correlative histological images may not exactly match the angiographic stenosis. However, this would lead to a decreased stenosis on histology measurement, suggesting that our results may actually underestimate the discrepancy. Of note, our angiographic stenosis is based on a proximal normal diameter as the denominator, while histological analysis uses the true diameter at the level of the lesion.

A mean of 53 days was present between angiography and amputation. Since atherosclerosis is a long-term process, we doubt significant changes to atheroma burden or architecture could occur in this short time span for the variables that we studied. Lastly, despite prompt harvest and preparation of the arterial specimens, perfusion fixation may not preserve the arterial architecture. Based on qualitative review of histological slides, we believe this is unlikely and that the arterial architecture is maintained.

Conclusion

Angiography provides us mostly with arterial luminal information, i.e., lumenography. The qualitatively deduced impression of concentricity and calcification of arteries is discordant with the arterial pathology. Recent evidence indicates high rates of reintervention after lower extremity angioplasty,¹⁵ which may be due to the underestimation of atheroma burden during the initial procedure. The average size of the popliteal vessel is nearly 7 mm and the tibial arteries ~3 mm. This information may aid in sizing of balloon angioplasty catheters as well as other adjunctive endovascular devices during peripheral interventions of popliteal and tibial arteries. Optimizing device sizing may translate to improved durability of these interventions by avoiding undersizing. Finally, the results of our study imply that adjunctive imaging modalities, including IVUS, in addition to angiography may be useful in the evaluation of patients with PAD.

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