Dynamic Forces in the SFA and Popliteal Artery During Knee Flexion

Consequences of stress to consider for stent durability and design.

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The superficial femoral artery (SFA) lies largely within the adductor canal, where it is surrounded by a double layer of fascia of the firm muscles of the thigh. After passing the adductor hiatus, the termination of the adductor canal, the SFA becomes known as the *popliteal artery* and enters the soft fatty tissue of the popliteal fossa. The SFA is hypothesized to undergo dramatic nonpulsatile deformations in the adductor canal, including axial compression and extension, radial compression, bending, and torsion. Because the SFA is largely untethered compared to the iliac and femoral arteries, which are tethered by the hypogastric arteries and the profunda femoris and the popliteal artery, which is tethered by the genicular arteries, the SFA is thought to be very susceptible to these deformations.[1]

Atherosclerosis commonly develops in the SFA. Scholten and coauthors found 72% of the femoropopliteal occlusions in their study at the level of the adductor canal hiatus (Figure 1).[2] Wood and coauthors showed that the adductor canal is a region with low wall shear stress (WSS), which is associated with atherogenesis.[3] Bypass surgery is the definitive solution for patients with atherosclerotic lesions of the SFA, but this invasive intervention is associated with long hospitalization and higher morbidity and mortality rates. Therefore, particularly in early-stage and short lesions, endovascular therapy is recommended in SFA disease cases.

Recently introduced self-expanding nitinol stents have shown improved patency results for femoropopliteal revascularization;[4-7] however, nitinol stent fractures in the SFA occur in 8% to 28% of cases and may cause complica-

tions, such as restenosis, pseudoaneurysm, perforation of the vessel, and embolism in the stent.[8-12] Longer stents, and especially multiple overlapping stents, which are often required by the long diffuse atherosclerotic lesions of the SFA, are associated with a higher stent fracture rate.[8] Furthermore, Iida et al proved that nitinol stent fracture was more frequent in patients who walked more than
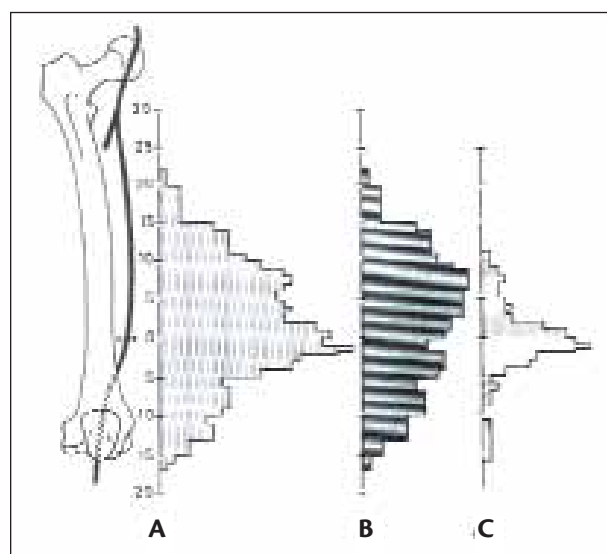

Figure 1. Location of the femoropopliteal occlusions related to the level of the adductor canal hiatus (zero level). Location of 50 femoropopliteal occlusions (A), location of long occlusions 5 to 25 cm in length (n=24) (B), location of short occlusions 1 to 5 cm in length (n=26) (C). (Reprinted with permission from Scholten FG, et al. Eur J Vasc Surg. 1993;7:680-683.)

5,000 steps a day compared with patients who did not exercise (*P*=.0027).[9] It is hypothesized that a high rate of stent fracture in the SFA is related to mechanical fatigue as a result of dramatic, repetitive, nonpulsatile SFA deformations.

STRESSES ON THE SFA

Certain dynamic forces experienced in the SFA during walking or knee flexion are unfavorable for stent durability. What exactly are these forces during knee flexion, and how should they affect stent design?

Shortening and Length Excess

Chivers and coauthors found that arteries tend to elongate with increasing age, and the femoral and popliteal arteries in patients with peripheral vascular disease elongate more than in controls of the same age.[13] In knee extension, the SFA shows a smooth, elongated S shape.[14] Because the adductor region is located close to the knee joint, flexion of this joint will certainly influence local morphology. As a result of the location of the artery in the lower limb, behind the axis of movement in the knee joint, there will be an excess of length in flexed position (Figure 2). During flexion, the artery bends smoothly instead of acutely and takes a shortcut, amplifying the relative length excess.[15]

In studies with limbs of human cadavers, the SFA is reported to shorten approximately 23% to 25% during 90° knee flexion[16] compared to 14% shortening in the popliteal artery.[17] In vivo, Cheng et al found that the mean SFA was 13% shorter in fetal position compared to supine position, using magnetic resonance angiography (MRA).[1] This length excess is compensated by tortuosity and typical curves (Figure 3). After stent placement in the femoropopliteal segment, the stented segment shortens less than the unstented artery during flexion of the hip and the knee. The unstented artery will shorten and bend more to accommodate the more rigid stented portion of the femoral or popliteal arteries. As the stented segment increases, the bare artery will shorten more during flexion. In overlapping stents, the overlapped portion becomes fixed and rigid and cannot shorten as much as the nonoverlapped stent.[17] This results in an increasing kink risk, particularly in the segments of the vessel and at the transitions to the stented segments, which will lead to intimal damage by shear forces, local progression of atherosclerosis, and impaired patency.[18]

Arterial Tortuosity

Wensing et al evaluated the morphology of the femoral artery during flexion and extension of the knee in vivo by examining 22 healthy volunteers with MRA.[15] They
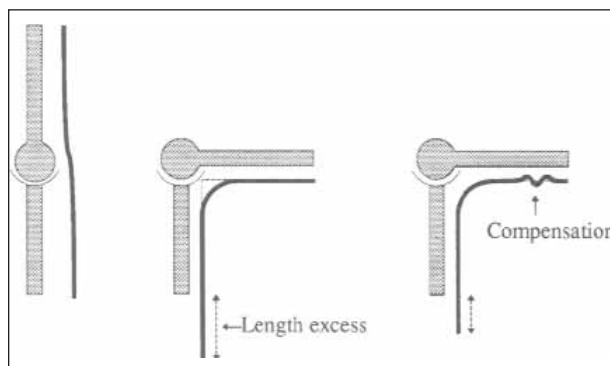

Figure 2. Relative length excess of the femoral and popliteal arteries during flexion of the leg, partly compensated by arterial tortuosity. (Reprinted with permission from Wensing PJ, et al. J Anat. 1995;187[Pt 1]:133-139.)

showed that the femoral and popliteal arteries became tortuous during knee flexion in all volunteers. In participants younger than 30 years old, all the curves in the femoral and popliteal arteries during knee flexion were located proximal to the adductor canal hiatus in the adductor canal, whereas in older subjects, many of these curves were located distal to the adductor canal hiatus. This occurrence could be explained by the fact that the natural gliding of the femoral vessels in the double layer of fascia in the adductor canal is impaired in the elderly due to perivascular fibrosis. Free movement of the SFA in the adductor canal is necessary to avoid traction to the vessel wall.[19] Moreover, the compensatory curves of younger subjects were only seen in the coronal plane because they were restricted to the shape of the canal plane. Curves located distal to the adductor canal hiatus, as seen in older subjects, have a nonplanar freedom of movement within the popliteal fossa. The radius of these curves decreased with increasing years (Figure 4), suggesting that in older individuals, the artery used the available space more efficiently. In all subjects younger than 45 years old, the artery regained its smooth, elongated S shape when the knee was extended. In older subjects, however, this original S shape was not completely restored in extension, and two or more small curves remained visible. The fact that arteries tend to elongate and lose their elasticity with increasing age could explain these differences in tortuosity between younger and older subjects.[13,15,20]

Axial Twisting

Cheng et al quantified the deformations of the SFA during the fetal position, which requires maximum knee and hip flexion, with MRA.[1] They calculated that in the fetal position, the SFA twisted with an average of 60°±34° compared to the supine position. The left SFA tended to turn

counterclockwise in the fetal position, whereas the right SFA mostly turned clockwise. They speculated that this twist was the result of the articular branch of the descending genicular artery being pulled medially by the vastus medialis muscle during knee flexion.

Blood Flow, WSS, and Early Atherosclerotic Lesions

Elongation and decreased arterial elasticity could result in permanent disturbances of blood flow.[15] WSS is directly proportional to blood flow and blood viscosity and inversely proportional to the cube of the radius. Wood et al suggest that atherosclerotic lesions tend to develop at sites with low WSS, prominent secondary flows, or changing patterns.[3] Flow curvature is known to promote secondary motions with helical streamline patterns. Stonebridge and Brophy found a spiral flow pattern in infrainguinal vessels using angioscopy.[21] Furthermore, the investigators saw spiral folds of the endoluminal surfaces in most of the examined infrainguinal vessels, even in normal and minimally diseased arteries.[21] Wensing and coauthors investigated the distal part of 23 postmortem femoral arteries and made a three-dimensional reconstruction of the vessel wall with atherosclerotic lesions, which revealed a preferential helical pattern in the localization of atherosclerotic lesions in the adductor canal. The pitch of these helixes ranged from 14 to 33 mm (33º to 60º).[22] In contrast to the findings of Cheng et al,[1] the direction of the helix was clockwise in most of the left femoral arteries and counterclockwise in most of the right femoral arteries.

Wood and coauthors showed a strong relationship between increased tortuosity and disturbed hemodynamic patterns in the SFA. Regions of low WSS and disturbed flow were visualized, especially in the adductor canal and in man.[3] Periods of consecutive knee flexions, resulting in a tortuous SFA and disturbed hemodynamic patterns, could

cause atherosclerosis to progress. More than 50 years ago, Lindbom speculated on the influence of knee flexion on atherogenesis.[23] On the other hand, frequent movements of the leg resulting in changing arterial shape and redistribution of WSS could delay this atherosclerotic process.[15]

CLINICAL CONSEQUENCES

We described the multiple spectacular deformations of the SFA during knee flexion, including shortening, tortuosity, axial twisting, and its effects on blood flow, WSS, and atherogenesis. These substantial deformations of the SFA during knee flexion suggest that they may be the mechanism of fatigue and fracture of SFA stents.[1,15] Apart from the impossibility of preventing metal fatigue by decreasing extremity movement and knee flexion for patients with SFA stents, frequent movements of the leg are thought to redistribute WSS, which could delay the atherosclerotic process.[15] Knee flexion for longer consecutive periods should be avoided by patients who undergo femoropopliteal recanalization to support more favorable hemodynamics in the femoral and popliteal arteries.[15]

To prevent stent fracture and distortion at the stent junction and improve stent patency, stents should change in length and contour, similar to the corresponding arterial changes during extremity movement. Stents with greater axial and torsional flexibility should have better fatigue characteristics. The ideal stent should be flexible in all possible directions, except in diameter. A combination of high flexibility and high radial strength is desirable. Wensing and coauthors showed that the SFA makes sharp acute curves during knee flexion in older subjects—patients who have elongated arteries with decreased elasticity—evidence supporting the need for flexible stents with high radial strength in this population.[15] When treating longer atherosclerotic lesions, longer stents should be used instead of overlapping stents, which are associated with higher kinking and fracture risk.[8] Furthermore, stents must maintain contact and adhere to the atherosclerotic vessel wall at all times, especially during knee flexion, to keep their intended location and shape. Wensing et al found that when treating spiraling lesions, stents should match this endoluminal surface.[22] Therefore, it could be advantageous for SFA stents to have a spiral design in addition to axial flexibility to endure axial twisting of the SFA. Naturally, this speculation should be confirmed by additional research.

CONCLUSION

SFA deformations have proven to differ between young and old subjects and patients with arterial disease and healthy people. Moreover, because muscle geometry and arterial branching vary substantially among the popula-

Figure 3. The femoropopliteal trajectectory during knee extension and flexion using angiography.

Figure 4. MRA showing the lateral view of the femoral and popliteal arteries during 80º flexion in a 30-year-old subject with a smooth curve from thigh to calf (A) and a 68-year-old subject with a sharp acute curve from thigh to calf (B). (Reprinted with permission from Wensing PJ, et al. J Anat. 1995;187[Pt 1]:133-139.)

tion, SFA deformations cannot be assumed to be similar in different people.[1] Functional angiography during knee flexion might be useful in planning stent placement in accord with individual segmental tortuosity. If extensive kinking occurs during functional angiography, the patient should either be excluded from stent placement or receive a more elastic or shorter stent.[17,24] ■

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