ARTERIOVENOUS FISTULA, PART 3: PHYSIOLOGIC TESTING IN ISCHEMIC STEAL SYNDROME

INTRODUCTION
Access for hemodialysis can be hampered by durability issues, recurrent stenoses, and central venous occlusions that shorten patency and can result in significant quality of life issues. However, the most severe and feared complication of hemodialysis access has less to do with the durability of the access than of arm and hand ischemia caused by the access itself. Ischemic steal syndrome results from hypoperfusion and ischemia of the forearm and hand due to arterial flow through the fistula that “steals” blood flow from the high resistance distal tissues and shunts it into the low resistance fistula or graft. Steal syndrome has a variety of symptoms related to hypoperfusion of the hand and forearm, ranging from paresthesias and discomfort only when on dialysis to constant pain, wasting of the finger muscles, loss of motor function and distal ulcerations. A substantial amount of hemodialysis patients with a permanent access (graft or fistula) have some kind of physiologic steal syndrome, but steal causing severe ischemic symptoms requiring intervention is rare and only present in 1-8% of AV fistulas. Steal can develop immediately after the creation of the AV access, requiring close monitoring or return to the operating room for revision or ligation. The condition can also develop insidiously over time as the access outflow veins mature and the amount of blood shunted from the arterial to the venous circulation increases. Steal tends to develop with more proximal AV fistulas and grafts due to the presence of a larger donor artery. Noninvasive methods of peripheral arterial assessment can identify patients with steal and support the diagnosis based on physiologic measurements.

DIGITAL PHOTOPLETHYSMOGRAPHY FINGER PRESSURE MEASUREMENT
The diagnosis of steal syndrome, especially if it is of insidious onset, can sometimes be difficult to quantify based on physiologic testing alone. Clearly the presence of symptoms on the side of an AV access warrants a workup but several differential diagnoses for hand ischemia must be considered, and physiologic testing can help differentiate them and guide further workup. The two types of physiologic testing utilized for diagnosis of steal syndrome are finger pressure monitoring/plethysmography and duplex ultrasound.

Finger pressure monitoring is performed using individual pressure cuffs on each finger (or, more practically in most labs, a single cuff measuring the pressure sequentially on each finger). A baseline measurement is performed, then the fistula is compressed (if possible) and measurements performed again. Baseline pressures of less than 60mmHg are associated with abnormally low perfusion to the fingers. This has been demonstrated to have a diagnostic accuracy of greater than 90% for the diagnosis of ischemic steal.

The ratio of digital pressures to brachial pressures, or digital-brachial index (DBI) can also be measured and reported. The brachial artery pressure is measured in the standard fashion using a blood pressure cuff around the ipsilateral upper arm. The ratio of the highest digital pressure to the brachial pressure is
reported as the DBI. Although intuitive and easily calculated, this measurement can be relatively inconsistent with clinical presentation. Multiple manuscripts and authors have proposed cutoff values for the diagnosis of ischemic steal that range from 0.4-0.6, but the same studies have also noted that patients with a low DBI can also be asymptomatic. Mohamed and Peden have noted that the presence of a high DBI may potentially be more important than the presence of a low DBI as it effectively rules out the presence of ischemic steal\textsuperscript{1}, with a high negative predictive value of 97%.

The measurement of digital pressures is performed using digital plethysmography\textsuperscript{2}. Digital plethysmography utilizes a light emitting diode to transmit infrared light into the tissue. The frequency of the transmitted light is tuned such that reflected light from circulating red blood cells within blood vessels can be measured by a photodetector built into the pressure cuff. The photoplethysmograph photodetector is a small sensor unit that is usually attached to the strap of a digital pressure cuff. The cuff is attached to the digit to be examined with the light emitting diode and detector against the pad of the digit. Digital pressures can be obtained by inflating the cuff until the amplitude of the plethysmographic waveform flattens. The electrical resistance within the photodetector varies depending on the amount of blood in the microcirculation at any given time - the amplitude increases with increasing numbers of red blood cells in the microcirculation and decreases as the amount of red blood cells decreases. The electrical changes in the detector can thus be taken as representative of blood volume variation over the cardiac cycle and plotted as a pulse wave.

This volume variation over the cardiac cycle can be plotted as a pulse wave recording and utilized as a secondary diagnostic tool for the identification of steal. These waveforms can be interpreted similarly to pulse volume recordings taken in the rest of the extremities. In the case of ischemic steal, digital pressures and waveforms should be obtained in all fingers on both sides. Data on the contralateral side can be useful as perfusion of the individual fingers can vary, especially in patients with incomplete palmar arches or other anatomic variability; the contralateral side can then serve as a control for comparison purposes.

Pulse wave amplitudes can be used independently as a predictor for ischemic steal. Amplitudes that are significantly blunted compared to those on the contralateral side can be suggestive of physiologic steal. Amplitude response, or an increase in the finger amplitude, after compression of the fistula are also indicative of steal - qualitative doubling of the amplitude after fistula compression is used in practice by some as a significant predictor of steal syndrome\textsuperscript{1}. It should be noted that pulse wave recording amplitudes do not have a quantitative component and numerical measurements cannot be assigned to the waveforms; they are purely a qualitative measurement and are subject to interpretation\textsuperscript{2}.
Figure 1. Bilateral plethysmographic waveforms and finger pressures during a diagnostic steal study. The left arm waveforms are blunted and diminished in amplitude compared to the right. However the digital pressures are similar. This patient ultimately underwent a DRIL procedure with resolution of symptoms.

Figure 2. Plethysmographic waveforms before and after finger compression showing minimal change.

EVALUATING ARTERIAL INFLOW LESIONS

A positive finger pressure evaluation only represents significant reversible ischemia. Worsening of physiologic steal from an AV fistula or graft to become clinically significant can be caused by a proximal arterial inflow obstruction such as an atherosclerotic lesion limiting flow into the arm. Identifying troublesome arterial inflow lesions requires duplex ultrasound of the upper extremity arterial system. Upper extremity arterial lesions can be identified using the standard diagnostic criteria, including
elevated peak systolic velocities or velocity ratios, and delayed upstroke “tardus-parvus” spectral waveforms distal to the stenosis. Native inflow arterial lesions can be an often-overlooked cause of steal syndrome and should be considered in all cases, especially since hemodialysis patients are prone to developing calcification within the arterial walls causing eventual hemodynamically significant stenosis. Any lesions identified on duplex examination should be interrogated using contrast arteriography with consideration for further intervention.

Duplex examination of the arterial tree can also help to confirm the clinical diagnosis. Physiologic changes after creation of an arteriovenous fistula have been well demonstrated in the literature, with many published instances of reversal of flow in a distal artery in order to feed the fistula or graft. This may present differently depending on the location of the anastomosis – in a radiocephalic AV fistula, for example, the distal radial artery would exhibit retrograde flow as it feeds the fistula via forward flow in the ulnar and collateralization through the palmar arch. Steal in a brachial artery-based access may result in one or both distal arteries with reversed flow. However, these findings are not universal and some patients with ischemic steal may present with no reversal of flow but low velocities and tardus parvus waveforms in the setting of a proximal lesion. The presence of reversal of flow and subsequent physiologic predisposition to steal also does not carry high specificity for the diagnosis of steal; several studies have demonstrated that simply having reversal of flow in the artery distal to the fistula or graft does not equate to clinical symptoms of steal.

Therefore, although evaluation of the arterial system in a patient suspected of having ischemic steal syndrome must involve the outflow vein and anastomosis as well as complete imaging of the proximal inflow vessels and close examination of the radial and ulnar arteries as distally as possible, in order to acquire enough information for the clinician to make a diagnosis of steal and to either make an informed therapeutic decision or to obtain more imaging. It is important to remember that physiologic testing can support the diagnosis of ischemic steal but findings may sometimes be inconsistent; when in doubt, reliance on the clinical diagnosis is adequate.

SURGICAL REVASCULARIZATION FOR STEAL SYNDROME

Although much study has been performed on the prevention of steal syndrome, prophylactic methods and precautions have been insufficient in preventing cases of steal. Recommendations for the prevention of steal during the initial access creation surgery have included using the most distal artery possible, varying the angle of the anastomosis and/or limiting the size of the arteriotomy to less than 7mm. Several options exist for surgical treatment of ischemic steal syndrome. Ligation of the AV fistula is the most definitive treatment but obviously results in sacrifice of the access. Banding was initially proposed to limit the amount of blood flow through an AV fistula in an attempt to prevent steal; however this method has been shown to be rather unreliable. All of the other alternatives involve revising either the anastomosis or the arterial segment proximal to the anastomosis, with the exception of fistula ligation which is not ideal but is a viable option when abandoning the access is preferred rather than risk further steal. Proximalization options (proximalization of arterial inflow, PAI) and distal revision (revision using distal inflow, RUDI) have been recognized to be viable options. However, the most common procedure and the one that most influences future physiologic and duplex ultrasound testing is the distal revascularization and interval ligation (DRIL) procedure.

Preoperative arteriography may assist in establishing a diagnosis of steal by identifying any proximal inflow arterial lesions. In addition, in a radiocephalic AV fistula, selective catheterization of the ulnar artery may demonstrate retrograde filling of the radial artery and AV fistula through the palmar arch. In
these specific situations, ligation of the distal radial artery may solve the steal problem without more invasive surgical intervention.

The DRIL procedure involves altering the arterial anatomy by creating a bypass from 10cm proximal to the access anastomosis to a point just distal to the access anastomosis, then ligating the artery in between. For instance, when performing a DRIL procedure for a brachiocephalic AV fistula, a bypass with saphenous vein would be constructed from 10cm proximal to the access anastomosis to either the brachial artery at the bifurcation, with ligation of the brachial artery just proximal to the distal insertion of the bypass. The long distance between the bypass takeoff and the anastomosis results in adequate pressure to drive perfusion into the bypass without compromising the flow to the fistula. The bypass is usually constructed with saphenous vein but prosthetic material can also be used. Results of DRIL are good, with series demonstrating 100% technical success with 98% reduction in clinical symptoms of steal and a low (7%) 30-day complication rate.

RUDI is a technique involving resiting of the AV fistula anastomosis further distally on the arterial tree. A brachiocephalic AV fistula, for example, would be revised into a proximal radiocephalic AV fistula. This can either be done by stretching the outflow vein onto the new artery if the previous anastomosis was close to the bifurcation, or by the addition of a jump or bridging graft comprised of either vein or prosthetic. PAI is a similar technique but involves re-siting the anastomosis proximally onto the proximal brachial or axillary artery. Both of these techniques depend on the properties of the new inflow arteries for the RUDI procedure, revision to a more distal branch artery and with a smaller anastomosis may lead to less blood flow stealing through the fistula. For PAI, the greater blood flow in the inflow artery proximally may allow an adequate amount of flow through the AVF while preserving flow into the distal arterial tree. The published literature has shown good results; RUDI procedures in recent series have shown greater than 80% secondary patency of the access at one year, with 90% showing either complete or partial improvement in clinical steal symptoms.

**IMAGING AND SURVEILLANCE AFTER SURGICAL REVASCULARIZATION**

The majority of patients have symptom resolution after surgical treatment of steal syndrome. Treatment options that involve revision of the anastomosis only, such as RUDI and PAI, do not require significant changes to imaging and surveillance protocols postoperatively. These patients can be followed outside of the perioperative period with imaging and testing whenever necessary based on access malfunction symptoms. Patients who undergo a DRIL procedure, however, now have a new brachial to brachial artery bypass which must be surveilled and must be recognized on future imaging of the access or arm vasculature. The DRIL bypass is imaged in the same way as an arterial bypass graft. It is important for the technologist and interpreting physician to note the velocities and waveforms in the inflow artery, throughout the bypass, and at and distal to the distal anastomosis, and to note any abnormal elevated or diminished velocities suggesting a failing graft.
ISCHEMIC MONOMELIC NEUROPATHY

Ischemic monomelic neuropathy (IMN) is a rare postoperative condition that can cause motor and sensory dysfunction. The presentation of IMN can mimic that of ischemic steal, and as such many cases may be misdiagnosed or have delayed diagnosis which results in severe and sometimes irreversible neuropathic symptoms or paralysis of the hand, fingers, and/or forearm. The classic presentation of IMN is pain and weakness or paralysis of the digits and/or hand without concomitant signs or symptoms of arterial insufficiency. Unlike physiologic steal, IMN does not involve diversion of significant amounts of blood flow in order to cause ischemia. Rather, it is thought to be related to microischemia of the upper extremity, primarily at the level of the small vessels perfusing distal nerve endings, although the exact pathophysiology remains poorly understood. Standard treatment for IMN is immediate return to the operating room for ligation of the access. IMN is clinically diagnosed and differentiated from ischemic steal syndrome based primarily on physical exam. The presence of a palpable distal pulse (most often the radial pulse) is suggestive of adequate distal perfusion, decreasing the likelihood of ischemic steal. The diagnosis of IMN can also be supported with a point-of-care duplex ultrasound exam - if there is normal or near-normal waveforms, velocities, and direction of flow in the radial and ulnar arteries then IMN is suspected and immediate ligation of the access, rather than revision or DRIL procedure, is indicated.

CONCLUSIONS

Physiologic steal is present in many patients with hemodialysis access due to a high pressure arterial inflow feeding a low pressure venous system. However, development of ischemic steal symptoms is limited to a selective cohort who have either diverted a significant amount of flow through the AV fistula resulting in severely diminished digital pressures, or those who have developed proximal arterial lesions restricting flow into the arm. In either case, those with symptomatic steal must undergo either ligation of the fistula or other surgical intervention and as such early diagnosis is paramount.

REFERENCES

1) S68–73.


