The MILLER banding procedure is an effective method for treating dialysis-associated steal syndrome

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We evaluated the efficacy of the Minimally Invasive Limited Ligation Endoluminal-Assisted Revision (MILLER) banding procedure in treating dialysis-associated steal syndrome or high-flow access problems. A retrospective analysis was conducted, evaluating banding of 183 patients of which 114 presented with hand ischemia (Steal) and 69 with clinical manifestations of pathologic high access flow such as congestive heart failure. Patients were assessed for technical success and symptomatic improvement, primary and secondary access patency, and primary band patency. Overall, 183 patients underwent a combined 229 bandings with technical success achieved in 225. Complete symptomatic relief (clinical success) was attained in 109 Steal patients and in all high-flow patients. The average follow-up time was 11 months with a 6-month primary band patency of 75 and 85% for Steal and high-flow patients, respectively. At 24 months the secondary access patency was 90% and the thrombotic event rates for upper-arm fistulas, forearm fistulas, and grafts were 0.21, 0.10, and 0.92 per access-year, respectively. Hence, the minimally invasive MILLER procedure appears to be an effective and durable option for treating dialysis access-related steal syndrome and high-flow-associated symptoms.

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On the creation of a hemodialysis access, a low-resistance venous pathway is connected to the arterial circuit. This creates the potential for several problems, which cover a spectrum of disease from dialysis-associated steal syndrome (Steal) to high-output cardiac overload. The ideal access functions with just enough pressure and flow to prevent thrombosis while maximizing hemodialysis efficiency. The range of blood flow within a typical dialysis access can be divided into low ($<$600 ml/min), normal (600–1500 ml/min), and high (1500–4000 ml/min) categories.[1] However, the range of flow in the access has very little correlation with patient symptoms. A low-flow access ($<$600 ml/min) can cause both Steal and cardiac overload, depending on the degree of pre-existing systemic vascular disease and cardiac dysfunction. Conversely, a high-flow access (1500–4000 ml/min) may cause neither Steal nor cardiac overload symptoms.[2] Proposed treatments are entirely based on clinical symptoms rather than attempts to normalize access flow.

Steal syndrome develops in 2.7–4.3% of arteriovenous grafts (AVGs) and 1% of arteriovenous fistulas (AVFs).[3,4] It is clinically defined as hypoperfusion distal (more peripheral) to the hemodialysis access due to the access diverting an excessive amount of blood away from the distal artery (Figure 1). Increased resistance in the distal arteries (microvascular and macrovascular disease) contributes to the diversion of blood into the AV access, exacerbating distal hypoperfusion and frequently resulting in ischemic symptoms.[5] If untreated, Steal can lead to debilitating neuropathy and tissue loss.

High flow within an AV access develops over time. As the AV access ages, increased flow within the artery and vein induces dilatation, resulting in a gradual reduction in resistance.[6] The resultant high-flow circuit potentially leads to prolonged post-dialysis bleeding, problematic elevation of venous pressures, pathologically accelerated access growth, and cardiac overload.[2,7]

Banding is a technique that has commonly been used to correct these access dysfunctions by reducing access flow. The introduction of a high-resistance band is a reasonable

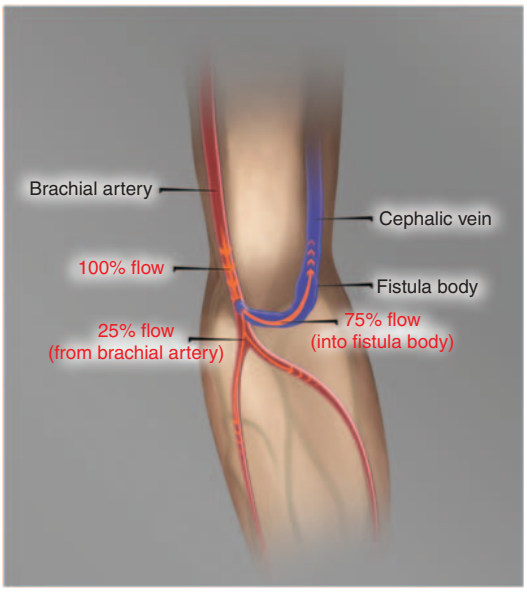

Figure 1 | Steal syndrome in a brachiocephalic fistula with distal hypoperfusion.

treatment for a low-resistance venous pathway, which has transformed a functional access into a pathologic shunt. Banding of these accesses was first described[8] shortly after the introduction of AV shunts for hemodialysis.[9] Various banding techniques have been described in published studies,[10–13] but complexities in sizing the band[14,15] and the resultant poor long-term outcomes have led to near abandonment of banding[16] and the development of alternative treatments such as distal revascularization with interval ligation (DRIL)[17] and proximalization of the arterial inflow (PAI).[18]

We are presenting the development of a precision modification to traditional banding procedures. The original Minimally Invasive Limited Ligation Endoluminal-Assisted Revision (MILLER) study included a cohort of 16 patients and treatment was confined to patients showing Steal symptoms.[19] Since its introduction, we have extended the use of the MILLER procedure to treat the full spectrum of low-resistance pathologic flow from Steal to High Flow within the access.

RESULTS

Outcomes

The incidence of Steal and High Flow requiring treatment in our practice was ~6%. The 183 patient cohort contained 156 upper-arm accesses (78 brachiocephalic AVFs, 58 transposed brachiobasilic AVFs, and 20 AVGs) and 27 forearm accesses. A total of 114 patients were classified as Steal and 69 patients were classified as High Flow.

An access band was created (technical success) in 225 of 229 (98%) of banding attempts. Overall, 89% of Steal and 94% of High Flow patients achieved clinical success (complete symptomatic relief) with the initial banding, and 96% of Steal and 100% of High Flow patients ultimately attained clinical success with one or more bandings. The most common first band size was 4 mm (57%) diameter (range, 2.5–6 mm) for fistulas and 3 mm (52%) for grafts (range, 3–4 mm). The total procedure time from initial access cannulation to closure of the skin ranged from 30 to 90 min.

Of four technical failures, three were due to instances of access bleeding, which led to abandonment of the procedure, and rebandings were successfully performed ~3 weeks later. In the fourth patient, the arterial anastomosis was located under the usable portion of the fistula body; this access was subsequently banded by the MILLER sizing technique during an open surgical procedure.

Clinical success was not achieved in 17 (9%) of our initial bandings, with patients experiencing only partial improvement. Of the 183 (7%) patients, 12 achieved clinical success with two or three banding attempts. Of the remaining five patients, three continued to use their access with partial (but tolerable) symptomatic relief and two required access ligation owing to persistent steal and resultant tissue loss (Tables 1 and 2).

Steal patients requiring multiple bandings had a significantly lower prevalence of hypertension ($P = 0.003$). The most common angiographic findings were complete occlusion of at least one forearm artery and an incomplete palmar arch, with a frequency of 67% (versus 9% in the total Steal cohort). Distal occlusion of both the ulnar and radial arteries was present in the two patients who underwent access ligation owing to persistent steal.

High Flow patients were significantly younger ($t = 3.1$, $P = 0.002$) and had a decreased prevalence of diabetes ($t = 4.87$, $P = 0.001$) compared with the Steal cohort (Tables 1 and 2). Overall, 100% of High Flow patients requiring multiple bandings had angiographically shown proximal brachial artery hypertrophy beyond 9 mm diameter (versus 29% in the total High Flow cohort and 0% in the Steal cohort).

The mean follow-up time was 11 months (range, 0.25–37). Steal and High Flow patients received percutaneous interventions at a rate of 2.96 and 3.53 per access-year, respectively. The most common post-banding intervention was angioplasty of venous outflow stenoses, accounting for 85% of interventions. Stretching of the band was performed at a rate of 0.10 and 0.34 per access-year in fistulas and grafts, respectively. In two patients with fistulas the banding site was problematic, requiring repeat angioplasty treatments (every 2–3 months). Banding-related thrombectomies (thrombosis within 30 days) were performed on 5 of 114 Steal and 1 of 69 of High Flow patients. All six patients had successful percutaneous thrombectomies. The thrombotic event rate for upper-arm fistulas, forearm fistulas, and grafts was 0.21, 0.10 and 0.92 per access-year, respectively. No aneurysms developed distal to the banding site.

The primary band patency for Steal and High Flow patients was 75 and 85% at 6 months, respectively (Figure 2). The primary access patency for Steal and High Flow patients was 52 and 63% at 3 months, with a secondary access

Table 1 | Patient demographics of the steal cohort[a]

	Complete improvement after 1 banding 101 (89)	Complete improvement after 2–3 bandings 8 (7)	Partial improvement after 2–3 bandings 3 (3)	Failure (access ligation owing to persistent steal) 2 (2)
Upper-arm fistulas	70 (61)	5 (4)	2 (2)	0 (0)
Forearm fistulas	12 (11)	0 (0)	0 (0)	2 (2)
Upper-arm grafts	19 (17)	3 (3)	1 (1)	0 (0)
Sex (M/F)	52/49	2/6	2/1	1/1
Hypertension	72 (73)	2 (25)	2 (67)	1 (50)
Diabetes mellitus	75 (76)	4 (50)	3 (100)	2 (100)
Average age (years)	62	65	66	65.5

Abbreviations: F, female; M, male.
[a]The numbers in parentheses are percentages; the values were rounded off and hence do not add up to 100%.

Table 2 | Patient demographics of the High Flow cohort[a]

	Complete improvement after 1 banding 65 (94)	Complete improvement after 2–3 bandings 4 (6)
Upper-arm fistulas	57 (83)	2 (3)
Forearm fistulas	4 (6)	2 (3)
Upper-arm grafts	4 (6)	0 (0)
Sex (M/F)	40/25	3/1
Hypertension	51 (78)	3 (75)
Diabetes mellitus	23 (35)	0 (0)
Average age (years)	56	53

Abbreviations: F, female; M, male.
[a]The numbers in parentheses are percentages; the values were rounded off and hence do not add up to 100%.

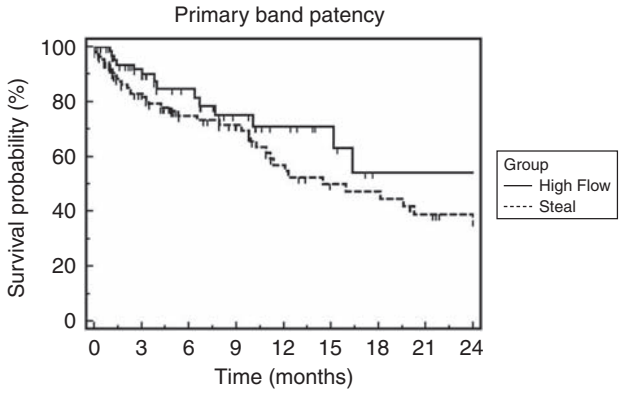

Figure 2 | Primary band patency for dialysis-associated steal syndrome (Steal) and High Flow patients (24 months).

patency of 90 and 89% at 24 months, respectively (Figure 3). The secondary access patencies of elderly (>65 years) and diabetics were not significantly different from the total cohort ($\chi^2 = 2.5$, $P = 0.11$ and $\chi^2 = 0.19$, $P = 0.66$, respectively). The secondary access patency of the 16 patients from the initial MILLER banding reports[19] was 77% at 36 months.

Three of our graft banding patients had previously undergone DRIL procedures and received 3 mm diameter bandings to augment effectiveness of the bypass. Five of our

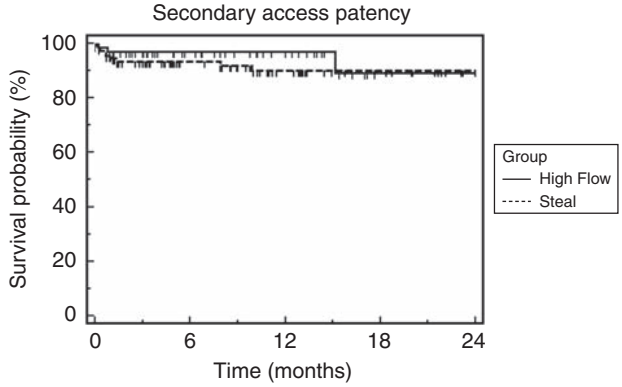

Figure 3 | Secondary access patency for dialysis-associated steal syndrome (Steal) and High Flow patients (24 months).

fistula banding patients had previously undergone traditional open surgical banding procedures and were rebanded using the MILLER technique.

Measurements

In a subset of patients, flow and pressure measurements were obtained. The average initial flow in Steal ($n = 8$) and High Flow ($n = 12$) patients was 2034 and 2629 ml/min, and the average flow reduction was 1046 (50%) and 1354 ml/min (52%), respectively. In Steal and High Flow patients ($n = 4$), the average initial intra-access pressure was 45 mmHg and the average pressure reduction was 23.5 mmHg (51.4%).

Follow-up

A total of eight Steal patients and two High Flow patients died during the follow-up period; however, their deaths were unrelated to the procedure and their accesses were patent at the time of death. Six patients had kidney transplants during follow-up.

Complications

Major complications occurred in two patients with AVGs and one patient with an AVF. These patients developed cellulitis, which spread from our transverse incision to the AV access, resulting in access ligation and graft removal within 14 days. The protocol was then modified to include antibiotic prophylaxis. In addition, the dissection technique was

modified to consist of two lateral incisions instead of one transverse incision (with full exposure of the access).[19] No infections occurred in the 179 subsequent procedures.

Minor complications included three cases of access (two AVFs and one AVG) bleeding during the procedure. These were treated with manual compression of the injured area until bleeding subsided, and did not result in delayed hemodialysis treatments. No patients required hospitalization or open surgical repair to control bleeding.

DISCUSSION

The introduction of a high-resistance band should correct steal and high flow in vascular accesses by diminishing access flow, and restoring sufficient distal arterial flow and perfusion. In accesses with normal to high flow, banding is appropriate but requires the operator to precisely control the diameter of the band.[14,15,20] Thermodilution-based flow measures are inaccurate when access flow reduction is used as a surrogate for distal arterial flow enhancement. Techniques such as finger plethysmography and the digital-brachial index[21,22] are measures of distal perfusion, but their utility is severely limited intra-operatively by changes in blood pressure, heart rate, and cardiac output experienced during administration of general anesthesia. When used as independent measures to adjust band size, they have suboptimal outcomes.[21] Combined, these techniques have yielded acceptable outcomes;[20,23] however, they cannot be standardized because of the influence of innumerable confounding variables and such results may not be easily reproducible by less experienced operators, using the same parameters.

The use of an intraluminal balloon as a sizing dowel is likely to prove useful not only for the minimally invasive MILLER procedure but also during open surgical banding procedures. The MILLER banding technique modulates band size with great precision, eliminating the need for complex flow and perfusion measurements. No expensive equipment or advanced measurement devices were needed for any patients. Using the sizing nomogram (Figure 4, Murray *et al.*[24]), the decision-making process is simplified to the creation of a band that results in a 60–80% reduction in lumen diameter. Therefore, 7-mm-diameter grafts were banded to 3 mm, and 20-mm-diameter upper-arm fistulas were banded to 5 mm. To overcome high distal arterial resistances, some forearm fistulas were banded to as little as 2.5 mm. In cases where the ligature size was inadequate, it was adjusted incrementally, as accesses were rebanded to a smaller size. In cases of access thrombosis, the bands were stretched, or even broken with a larger diameter angioplasty balloon. No significant vessel wall injury occurred after band breaking, as verified by follow-up angiograms.

Banding physiology is best explained by Poiseuille's Law, which states that fluid flow (Q) is proportional to radius (r), pressure across a gradient (ΔP, for example, arterial pressure−central venous pressure) and inversely proportional to resistances, length (L), and viscosity (η): $Q = (\Delta P \pi r^4)/(8\eta L)$. The MILLER banding technique decreases flow by decreasing the radius at a specific point and, as a result, access flow (Q_{access}) and pressure is directly sacrificed to increase distal arterial flow (Q_{distal}) and pressure. Therefore, in accesses with low-flow (low Q_{access}) steal, further flow reduction could lead to access thrombosis. These patients may benefit most from revasculatization procedures such as DRIL[17] and PAI,[18] which enhance total extremity flow and therefore enhance both Q_{distal} and Q_{access}.

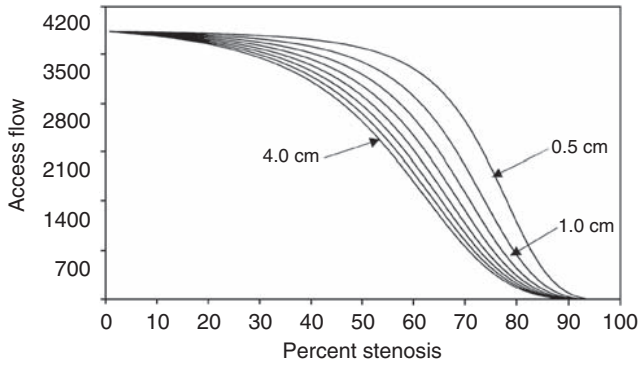

Figure 4 | Band sizing nomogram. Reprinted with permission from Murray *et al.*[24] The sigmoidal function lines represent arteriovenous fistulas of varying diameter (0.5–4 cm) and the percentage of lumen reduction necessary to significantly reduce total access flow.

In the first patients we treated, complete symptomatic relief was less important than avoidance of thrombotic events; therefore, we conservatively used larger intraluminal balloons (with a target of 60% lumen reduction) and then repeated the procedure in 4 weeks if residual symptoms persisted. With experience, estimation of initial band size improved, as we came to understand that clinical success could be more readily achieved (without inducing thrombosis) with a lumen reduction of ~75%. Flow measurements during the procedure have further improved the accuracy of our selection of initial band size.

In 9% of patients, rebandings were performed to enhance clinical efficacy. The majority of patients who required multiple bandings were Steal patients with low-normal blood pressure and High Flow patients with severe hypertension, as extremes of blood pressure made predicting the appropriate band size more difficult. During a rebanding, the resistance of a single band was augmented by placement of additional bands to create a segment of resistance rather than a focus of resistance. Such an increase in access resistance was necessary to overcome the high flow of a hypertrophic proximal artery in High Flow patients. Steal patients who required additional bandings ultimately achieved clinical success as resistance in the access increased beyond the peripheral resistance associated with arterial occlusions. When these arteries are occluded, the maximum Q_{distal} is decreased, and access flow must be reduced to a much greater extent in order to generate the flow and pressure necessary to divert a sufficient amount of blood to collateral arteries. In two Steal patients who required access ligation, the occlusion of both forearm

arteries made adequate Q_{distal} impossible to achieve without a reduction of Q_{access} that would make the access unusable.

Access interventions have historically been performed at rates as high as 5.3 per access-year for fistulas and 3.7 per access-year for grafts to decrease thrombotic events.[25] In our study, procedures were performed at a rate of 2.9 and 3.5 interventions per access-year in Steal and High Flow accesses, respectively. The primary access patency was 56% at 3 months, primarily due to the angioplasty of venous outflow stenoses.

Previous studies have obtained thrombosis rates of 1.1 per access-year in grafts[25] and 0.13–0.57 per access-year in fistulas.[25–27] Given these results, our thrombosis rates of 0.20 per access-year in fistulas and 0.92 per access-year in grafts are comparable with non-banding studies, suggesting that the MILLER method of banding does not compromise access durability in order to achieve the necessary flow reduction.

In our study, secondary access patency remained high after 24 months (90%). By comparison, the largest DRIL study to date (with grafts comprising 60% of accesses) obtained a 90% rate of clinical success (Table 3), with a 6% rate of thrombosis at an average follow-up of 7.4 months.[28] In that study, as well as others,[29] accesses with persistent Steal were ligated. We propose that the rate of DRIL clinical success can be further augmented through the application of the MILLER banding technique on such clinical failures, as three of our successfully treated banding patients had previously undergone DRIL procedures without complete symptomatic relief.

When approaching the banding procedure, the operator's initial concern is preventing and controlling access bleeding. The three instances of access bleeding we encountered were easily treated using focal pressure. In the event of bleeding, once hemostasis was achieved, a new dissection was generally started distal to the original site. A more distal dissection location was chosen to avoid exposing the injured area to the pressure gradient caused by the band. Using the same logic as applied to the access as a whole, aggressive treatment of venous outflow stenoses diminished intra-access pressure, which we believe minimized the potential for bleeding complications caused by a dissection injury.

Long-term potential complications include the development of intimal hyperplasia narrowing the banding lumen and aneurysms distal to the banding site. Aggressive intimal hyperplasia of the fistula lumen occurred in two patients and was treated with repeated balloon angioplasty across the region of the band. Despite a palpable pressure gradient distal to the band, no aneurysms developed. As all banding sites were confined to the distal access, no needle cannulations occurred in these areas. In addition, reduced intra-access pressure (mean reduction of 51.4%) proximal to the banding site appeared to attenuate further growth of mid-access cannulation-related aneurysms.[30]

The MILLER procedure is useful for all accesses exhibiting high flow and most accesses exhibiting steal syndrome. When selecting the optimal treatment for such access dysfunctions, the primary concerns are efficacy and invasiveness. The MILLER banding procedure is the least invasive of all current

Table 3 | Review of the literature

Study	Procedure	Indication	Access type	Patients (*n*)	Symptom resolution (%)	Secondary patency at 12 months (%)	Flow reduction (%)
Aschwanden *et al.*[35]	Banding	Steal	Fistula	3	100	100	68
DeCaprio *et al.*[36]	Banding	Steal	Graft	11	91	10	ND
Meyer *et al.*[37]	Banding	Steal	Fistula	7	100	ND	ND
Morsy *et al.*[3]	Banding	Steal	Fistula and graft	6	67	33	ND
Odland *et al.*[21]	Banding	Steal	Fistula and graft	16	100	39	ND
Schneider *et al.*[38]	T-banding	Steal	Fistula and graft	6	83	100[a]	45
		HF	Fistula and graft	20	95		49
Thermann *et al.*[39]	Banding	Steal	Fistula	25	68	65[b]	ND
Zanow *et al.*[20]	Banding	Steal and CF	Fistula	7	86	85	ND
Berman *et al.*[40]	DRIL	Steal	Fistula	21	100	94[b]	ND
Haimov *et al.*[41]	DRIL	Steal	Fistula	23	96	73	ND
Katz *et al.*[42]	DRIL	Steal	Fistula and graft	12	100	ND	ND
Knox *et al.*[28]	DRIL	Steal	Graft	52	90	83	ND
Korzets *et al.*[43]	DRIL	Steal	Fistula	9	100	ND	ND
Lazarides *et al.*[15]	DRIL	Steal	Fistula	7	94	ND	ND
Mwipatayi *et al.*[29]	DRIL	Steal	Fistula	12	92	100	ND
Schanzer *et al.*[44]	DRIL	Steal	Fistula and graft	14	83	100	ND
Sessa *et al.*[45]	DRIL	Steal	Fistula and graft	18	100	94	ND
Stierli *et al.*[46]	DRIL	Steal	Fistula	6	100	ND	ND
Zanow *et al.*[18]	PAI	Steal	Fistula and graft	30	84	90	ND
Presented data	MILLER banding	Steal	Fistula and graft	114	87	90	50
		HF	Fistula and graft	69	94	97	52

Abbreviations: CF, cardiac failure; DRIL, distal revascularization and interval ligation; HF, High Flow; MILLER, minimally invasive limited ligation endoluminal-assisted revision; ND, no data; PAI, proximalization of the arterial inflow; RUDI, revision using distal inflow.
[a]At 3 months.
[b]At 18 months.

treatments and its efficacy is now well established. As most accesses exhibiting steal symptoms will likely have sufficient proximal arterial flow, we believe the MILLER procedure ought to be the initial treatment for Steal. However, in cases of low-flow steal, DRIL or PAI may still be the optimal treatments. The precise sizing of MILLER banding provides a rapid way of achieving adequate balance between Q_{access} and Q_{distal} without diminishing access longevity over the 11-month average follow-up time of the study.

MATERIALS AND METHODS

Patient population

The patients were referred to 10 outpatient clinics in New York and New Jersey by over 40 surrounding dialysis centers with an estimated 10,000 dialysis lives. A total of 183 consecutive patients (100 male and 83 female) who adhered to the inclusion/exclusion criteria were treated with the MILLER banding procedure towing to steal syndrome and high-flow fistulas between February 2005 and April 2009. The banding procedures included in this study were performed by 10 interventionalists, with experience levels ranging from 1 year (for interventional nephrologists) to 30 years (for interventional radiologists).

All patients provided written informed consent for the banding procedure. No institutional review board existed at the author's institution at the time the study was initiated; therefore, the principles of the Declaration of Helsinki were followed. A retrospective analysis of patient records, digital images, and reports was conducted. All relevant patient data (including demographics, access type, symptoms, procedural complications, and access use at dialysis) were recorded for each patient.

Inclusion/exclusion criteria

Patients were evaluated and categorized as 'Steal' or 'High Flow' according to their symptoms and physical examination.

Steal. A diagnosis of steal was established on clinical grounds. Accesses were banded if they exhibited classic steal symptoms such as numbness and coldness of the hand, which were exacerbated at dialysis and alleviated by temporary shunt occlusion. The hand and fingers were generally most symptomatic, but cramping and pain of the muscles of the forearm and upper arm were also encountered. Signs of steal ranged from pallor to tissue necrosis of the hand and fingers. Angiography was then performed to confirm the diagnosis.

High flow. Diagnosis of a high-flow access was established on clinical grounds. High-flow accesses were banded if the patients developed decompensated congestive heart failure directly attributable to AV access placement, visibly notable aneurysm growth, or problematic elevation of venous pressures at dialysis.[6,31] Patients with simultaneous symptoms of both steal syndrome and high-access flow were categorized as High Flow.

All patients who underwent banding after classification into the Steal and High-Flow groups were included in the study. Patients with limb ischemia related to proximal arterial stenoses, or arterial stenoses amenable to angioplasty were excluded from the study.

Outcome definitions

Technical success was achieved when a band was created and the patient underwent at least one successful hemodialysis treatment. Any patient who achieved complete symptomatic improvement was considered to have clinical success. Patients who experienced partial (but adequate) symptomatic improvement were classified as having partial improvement. A thrombectomy procedure performed within 30 days of the initial banding was considered to be banding-related.

Complications

Major complications were defined as any adverse sequelae that resulted in fistula ligation, graft excision, open surgical repair of bleeding, or hospitalization. Minor complications were defined as those that did not interfere with hemodialysis treatments.

Primary and secondary patency statistical analysis

The Society of Interventional Radiology (SIR) reporting standards for primary access patency and secondary patency were used. Primary access patency is defined as the time between the initial access intervention and any following repeat interventions. Primary patency of the MILLER band ended with balloon dilation of existing bands, rebanding, or access thrombosis. Secondary patency is defined as the time of patency from the initial intervention until the access was surgically revised, abandoned, or until transplantation, death, and loss to follow-up.[32] A Kaplan–Meier analysis was carried out to construct a life-table estimate of fistula patency and band patency. χ^2-Tests were used to test for the association between secondary access patency and demographic characteristics of the patients. Unpaired *t*-tests were performed to assess the relationship between demographics and cohort classification.

Procedure

Angiography/pre-banding interventions. Access was gained into the AVF/AVG toward the arterial inflow using a 21-g microaccess needle and catheter (Cook, Bloomington, IN, USA). Imaging (GE OEC 9800 Plus, GE Healthcare, Salt Lake City, Utah, USA) using intravenous contrast (Ioxilan 62%, 300 mg/ml; Guerbet LLC) of the venous outflow was first performed to identify outflow obstruction. A 5F vascular sheath (Pinnacle, Terumo Medical, Elkton, MD, USA), 0.035-inch guidewire (Merit Medical Systems, South Jordan, UT, USA), and a Bern catheter (Boston Scientific, Natick, MA, USA) were used to gain access into the inflow artery and perform arterial imaging. With the catheter in the proximal feeding artery, extremity angiography was performed. If no contrast flow was visualized distal to the access anastomosis, contrast imaging of the distal arteries was performed with access compression to enhance contrast filling of these arteries. All Steal patients underwent an upper extremity arteriogram and any diagnosed flow-limiting axillary or brachial proximal arterial lesions were treated with angioplasty (Ultra-thin Diamond Balloon, Boston Scientific/Meditech, Watertown, MA, USA) and stent (Protégé EverFlex, ev3, Plymouth, MN, USA) placement, as needed. Diffuse distal disease of the ulnar and radial arteries was not treated.

Selection of the banding site. Palpation was used to find a site adjacent to the arterial anastomosis where the access body was mobile beneath the skin, indicating that the vein was free of adherent scar tissue. Ultrasound (Terason, Burlington, MA, USA) was used to determine access depth and the presence of adjacent vascular structures. Angiography confirmed the location of the arterial anastomosis and the size of the inflow artery, downstream arteries, and diameter of the banding site. The goal was to find a location in which the banding site would be as close to the anastomosis as possible, yet superficial enough to facilitate an easy dissection. In most cases, banding was performed within 1–3 cm of the arterial anastomosis (Figure 5).

Dissection. The procedure was performed using local anesthesia (1% xylocaine) and intravenous conscious sedation with Fentanyl (fentanyl citrate 50 μg/ml; Hospira, Lake Forest, IL, USA) and Versed (Midazolam HCl 2 mg/2 ml; Hospira). Intraprocedural monitoring of blood pressure, electrocardiogram, and pulse oximetry was performed (Datascope Passport 2, Datascope, Paramus, NJ, USA).

The original technique involved a transverse skin incision with full exposure of the access. The current minimally invasive technique involves two parallel, lateral 0.5 cm incisions, with a peri-access tunnel dissected subcutaneously using Kelly clamp blunt dissection (Figure 6). If incisional bleeding from the surrounding tissue was encountered, hemostasis was achieved using 2–3 min of focal pressure. When more severe bleeding resulted from perforation into the access, prolonged (5–20 min) focal pressure was necessary.

Dissection was first performed under the access. A subcutaneous 2-0 monofilament ligature of Prolene (Ethicon, Somerville, NJ, USA) was then pulled under the access (Figure 6). The second part of the dissection was then under the skin, but over the access. The suture was then looped around the access (Figure 6). An angioplasty balloon was then inflated to 18 atmospheres of pressure in the area encircled by the loop of suture. The ligature was tightened around the balloon until there was no flow in the access (Figure 7). Six knots were tied to minimize slippage of the Prolene suture. Once the ligature was secured, the balloon was deflated and flow was restored. Next, the access was palpated to ensure that access flow was adequate.[33,34] During the most recent 20 procedures, pre- and post-procedure flow measurements (Flow Transonic, Transonic Systems, Ithaca, NY, USA) and pressure measurements (TruWave Disposable Pressure Transducer, Edwards Lifesciences, Irvine, CA, USA) were obtained to help guide the interventionalist.

Angiography confirmed the procedure was complete when an injection of contrast into the proximal artery showed enhanced contrast run-off into the distal arteries while maintaining flow into the dialysis access (Figure 8). Once complete, the incisions were closed with Dermabond (Ethicon, Somerville, NJ, USA) adhesive solution or 4.0 Vicryl (Ethicon) subcuticular sutures.

Balloon sizing. Balloon sizing was critical to the procedure. Two factors were instrumental in helping to size the band. In Steal patients, the band was equal to or smaller than the size of the downstream artery, to ensure that resistance of the access was significantly increased with respect to the resistance of the downstream artery. In High-Flow patients, the above rule applies, but a nomogram illustrating the relationship between access diameter to flow volume (Figure 4, Murray *et al.*[24]) was helpful. According to the nomogram, lumen diameter needs to be reduced by 60–80% in order to significantly affect the flow. Therefore, a visual estimation of the banding site (before the banding) helped determine the final lumen size needed to significantly reduce flow.

Banding modifications. Immediately after a band was created, the balloon was deflated and removed. Following band placement, palpation of access flow was the only tool used in the majority of cases. If the flow was too slow, then a balloon with a diameter that was 1 mm larger was used to stretch the band (the knots in the Prolene suture stretch to a small degree). If the patient reported no symptomatic improvement and angiographic evidence of steal

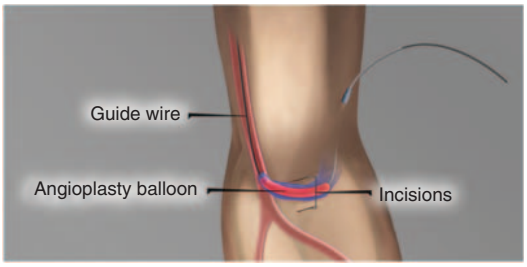

Figure 5 | An inflated angioplasty balloon is used as a sizing dowel inside the access. Two parallel, lateral 0.5 cm incisions are made approximately 1–3 cm from the arteriovenous anastomosis.

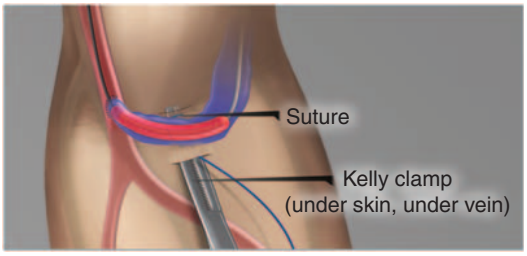

Figure 6 | A peri-access tunnel is dissected subcutaneously using Kelly clamp blunt dissection, and a 2-0 monofilament ligature of Prolene is pulled under the access.

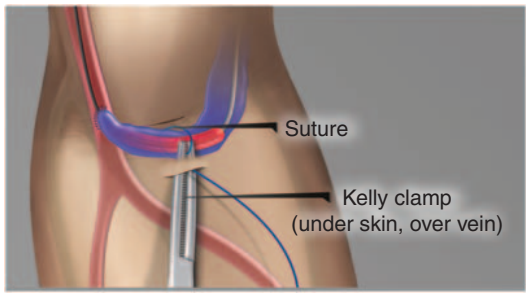

Figure 7 | The suture is looped over the access (under the skin) using a Kelly clamp.

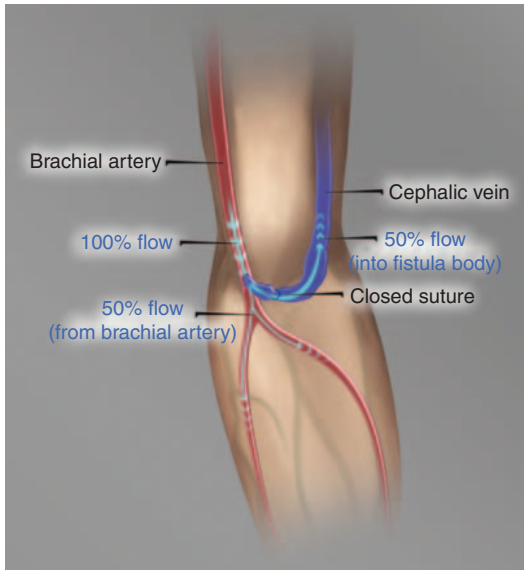

Figure 8 | Following the Minimally Invasive Limited Ligation Endoluminal-Assisted Revision (MILLER) banding procedure, the resistance band redirects flow, improving distal perfusion, and alleviating symptoms.

persisted, the procedure was repeated with a second ligature (using a balloon with a diameter 1 mm less than that of the first).

Medications. The minimally invasive dissection procedure was performed regardless of anticoagulation status (Warfarin; Clopidogrel). Anticoagulants (heparin) were not necessary during the procedure.

DISCLOSURE

All the authors declared no competing interests.

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