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Hemodialysis vascular access monitoring: current concepts

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Abstract

Most arteriovenous grafts fail due to irreversible thrombosis, and most clotted grafts have an underlying stenotic lesion. These observations raise the plausible hypothesis that, early detection of graft stenosis with preemptive angioplasty will reduce the likelihood of graft thrombosis. A number of noninvasive methods can be used to detect hemodynamically significant graft stenosis with a high positive predictive value. These tests include clinical monitoring, as well as surveillance by static dialysis venous pressures, flow monitoring, or duplex ultrasound. However, these surveillance tests have a much lower positive predictive value for graft thrombosis in the absence of preemptive angioplasty. In other words, none of the currently available surveillance tests can reliably distinguish between stenosed grafts destined to clot, and those that will remain patent without intervention. As a consequence, any program of graft surveillance necessarily results in a substantial proportion of unnecessary angioplasties. Moreover, a substantial proportion of grafts thrombose despite a normal antecedent surveillance test. Numerous observational studies have found an impressive reduction of graft thrombosis after implementation of a stenosis surveillance program. In contrast, 5 of 6 randomized clinical trials failed to show a reduction of graft thrombosis in patients undergoing graft surveillance, as compared with those receiving only clinical monitoring. The lack of benefit of surveillance is largely attributable to the rapid recurrence of stenosis after angioplasty. Thus, routine surveillance for graft stenosis, with preemptive angioplasty, cannot be recommended for reduction of graft thrombosis. Future research should be directed at pharmacologic interventions to prevent graft stenosis.

Introduction

To be effective in reducing graft and fistula thrombosis, the ideal program of noninvasive stenosis surveillance should fulfill three criteria: (1) the test should have a high positive predictive value for hemodynamically significant graft or fistula stenosis; (2) it should be able to distinguish between stenosed accesses destined to thrombose and those that will remain patent without intervention; and (3) preemptive angioplasty of stenosis detected by surveillance should reduce the likelihood of access thrombosis. This review will address each of these questions, to evaluate the usefulness of vascular access monitoring or surveillance as a tool for reducing graft and fistula stenosis and improving access longevity.

The primary focus of this review is on surveillance of grafts, for which there is much more published information.

Rationale for vascular access monitoring/surveillance

The cumulative patency of arteriovenous grafts is dismal, with the median time from graft creation to permanent failure being about 2 years [1, 2]. Given that the majority (~80%) of grafts fail due to irreversible thrombosis [3], improving graft longevity requires interventions to prevent or delay thrombosis. Permanent graft failure due to thrombosis is frequently preceded by one or more episodes of reversible thrombosis. At the time of thrombectomy, angiography frequently reveals an underlying, hemodynamically significant stenosis at the venous anastomosis, in the draining vein, or in the central vein [4, 5]. Less commonly, stenosis is present within the graft itself or at the arterial anastomosis [6, 7]. An anatomic cause is detected in > 90% of thrombosed grafts, suggesting that stenosis is nearly always a prerequisite for graft thrombosis.

Not all stenosed grafts are destined to clot. Lumsden et al [8] followed 32 patients with 50% graft stenosis documented by angiography. After 3 months without intervention, only 23% of the grafts had thrombosed. After 6 months, only 30% had clotted. Thus, stenosis is necessary, but not sufficient, to cause graft thrombosis. It would be desirable to identify noninvasive tests that can reliably predict grafts at risk for thrombosis. Targeted interventions in these grafts may improve long-term access outcomes.

Several observational studies have quantified primary (intervention-free) graft patency following elective angioplasty and after thrombectomy (**Tables 1 and 2**). Graft patency at 3 months was 37 to 63% after thrombectomy, as compared with 70 to 85% after elective angioplasty. At 6 months, the primary patency was 11 to 39% after thrombectomy, as compared with 47 to 63% after elective angioplasty. A large observational study compared the outcomes of all graft thrombectomies and elective angioplasties (>300 of each procedure) performed at a single medical center during a 3-year period [4]. Primary graft patency at 3 months was 30% after thrombectomy vs 71% after elective angioplasty. At 6 months, the primary patency was 19% after thrombectomy vs 51% after elective angioplasty. When the analysis was restricted to those grafts with no residual stenosis following the intervention, the median intervention-free graft patency was 2.5 months after thrombectomy vs 6.9 months following elective angioplasty.

The inferior patency of grafts undergoing thrombectomy as compared with those undergoing elective angioplasty argues for a proactive strategy to prevent graft thrombosis. Given that underlying stenosis is a major risk factor for graft thrombosis, timely detection and correction of stenosis may be more beneficial than waiting for a graft to clot before intervening. These considerations have led to the plausible hypothesis that preemptive (elective) angioplasty of hemodynamically significant (> 50%) stenosis will reduce the likelihood of graft thrombosis, and thereby prolong graft longevity. This hypothesis has been the subject of numerous research publications, including observational studies and randomized clinical trials.

Can noninvasive monitoring or surveillance predict graft stenosis?

The reference standard for the diagnosis of graft stenosis is angiographic characterization of the lesion. Because this is an invasive and expensive diagnostic procedure, one would like to identify a noninvasive test with a high positive predictive value for angiographically demonstrated stenosis. Such a test would permit efficient screening for grafts likely to have stenosis. Only those patients with an abnormal noninvasive test would be referred for a diagnostic fistulogram (and angioplasty, if stenosis is confirmed). The available noninvasive studies fall into two broad categories: clinical monitoring and surveillance [9].

Clinical Monitoring

Clinical monitoring refers to tests that are readily available from physical examination or review of laboratory studies obtained routinely in the dialysis unit [10-14]. These include (1) inspection, physical examination and auscultation of the graft and extremity (absent thrill, abnormal auscultation, or edema distal to the graft); (2) difficulties experienced during the dialysis session (difficulty in cannulation or prolonged bleeding from the needle site); or (3) an unexplained decrease in Kt/V over time on a constant dialysis prescription. Clinical monitoring has a relatively high (69 to 93%) positive predictive value for angiographically confirmed stenosis (**Table 3**). The positive predictive value varies for different components of clinical monitoring, being 80% for abnormal physical examination of the graft, 69% for an unexplained decrease in Kt/V; and 66% for abnormalities during the dialysis session [13]. Within the last category, the positive predictive value is 76% for prolonged bleeding from the needle sites, 58% for difficulty in graft cannulation, but only 30% for aspiration of clots[13]. The major advantage of clinical monitoring over graft surveillance is its low cost: it doesn't require additional equipment or dialysis personnel. However, the success of clinical monitoring in detecting graft stenosis is highly dependent on the proficiency of the dialysis staff and the consistency with which they monitor the graft. Thus, in 5 randomized clinical trials evaluating graft surveillance, the frequency of angioplasty in the control group (clinical monitoring) ranged from 0 to 0.64 events per patient-year [8, 13, 15-17].

Graft Surveillance

Graft surveillance refers to noninvasive methods requiring specialized equipment, specially trained staff, or both. Dialysis units that implement a graft surveillance program usually hire 1 or 2 trained technicians to perform the measurements. As a result, graft surveillance is likely to be performed more consistently than clinical monitoring, and the results are likely to be more reproducible. However, surveillance adds to the cost of operating a dialysis unit, and it is therefore incumbent to demonstrate that the added cost translates into improved graft patency. All graft surveillance methods are based on the premise that progressive graft stenosis will result in a predictable increase in the intra-graft pressure (normalized for systemic blood pressure) and/or a decrease in access blood flow. The three major forms of graft surveillance are static dialysis venous pressures, flow monitoring, and duplex ultrasound. Static dialysis venous pressure is measured by hooking a manometer to the arterial dialysis needle before starting the dialysis pump. The intra-graft pressure is normalized to the systemic blood pressure, and expressed as static venous pressure ratio

(SVPR). One would expect a progressive increase in SPVR as the magnitude of stenosis increases [18].

Flow monitoring uses the Fick principle of dye dilution to estimate access blood flow. The arterial and venous lines are reversed in orientation, and ice-cold saline injected rapidly through the arterial port. The higher the access blood flow, the faster the rise in blood temperature following the ice saline injection. By measuring the area under the temperature curve, the computer can calculate the access blood flow [19]. Theoretically, progressive stenosis should result in a progressive decrease in access blood flow. An access blood flow < 600 ml/min or a decrease in flow by > 25% from baseline is predictive of significant graft stenosis [20, 21]. Monthly flow monitoring of grafts has been proposed as the preferred stenosis surveillance method in the KDOQI guidelines [9].

Finally, duplex ultrasound can be used to detect graft stenosis by peak systolic velocity (PSV) measurements at anastomoses and sites with visual stenosis. The ratio of PSV at the stenotic site to PSV immediately upstream to the stenosis is calculated. A PSV ratio > 2.0 has an 80% positive predictive value for angiographically demonstrated stenosis [13]. Duplex ultrasound can also be used to measure the blood flow as a secondary supportive indicator of graft stenosis [22, 23]. Unlike static dialysis venous pressures and flow monitoring, this test currently cannot be performed at the dialysis unit and requires the patient to go a radiology department at a nearby hospital or clinic.

The false negative rate of noninvasive tests for hemodynamically significant stenosis is more difficult to determine. Calculating this value would require performing routine diagnostic angiograms in patients with normal monitoring/surveillance. Performing such a study would be difficult to justify ethically. However, the value can be inferred from the relatively high frequency of graft thrombosis that is not preceded by abnormal monitoring/surveillance testing, approximately 20-25% [24-26].

Can noninvasive surveillance predict graft thrombosis?

Although noninvasive surveillance tests are useful in detecting graft stenosis (Table 3), the more relevant clinical question is, how well do they predict graft thrombosis, if preemptive angioplasty is not performed? Several studies obtained baseline access flow measurement in dialysis patients with grafts, and then determined the natural history of the grafts (Table 4). Among grafts with a baseline access flow <500-700 ml/min, only 25 to 43% thrombosed during the subsequent three months of followup. Thus, a low access flow is much less predictive of future graft thrombosis than of graft stenosis. This means that any surveillance program for graft stenosis will inevitably result in a substantial number of unnecessary angioplasties on grafts that would not have gone on to thrombose. Given the variability in access flow measurements [27], a decrease in access blood flow over time may be a better predictor of graft thrombosis, as compared with an isolated low value. However, a prospective study reported that, among patients with a 25% decrease in access flow from baseline, only 26% experienced graft thrombosis during the ensuing 3 months [21]. Similarly, a recent study found the sensitivity and specificity of flow monitoring for graft

thrombosis was no better when the change in access flow was used, as compared with the absolute access flow [28].

The ideal surveillance test would distinguish between stenotic grafts destined to thrombose, and those that would remain patent. Such a test would result in preemptive angioplasty in most grafts likely to thrombose, while avoiding unnecessary interventions in grafts that would remain patent. In fact, angioplasty may predispose some grafts to thrombose earlier than they might have otherwise. Unfortunately, none of the currently available surveillance methods reliably perform in this manner. The mean access blood flow is statistically lower in grafts that will thrombose than in those that will remain patent [29]. Unfortunately, there is considerable overlap in the access flow values between the two groups, such that it is impossible to identify a threshold value to achieve adequate separation. Two observational studies evaluated the performance of stenosis surveillance tests in a group of dialysis patients with grafts followed prospectively without preemptive angioplasty. McDougal and Agarwal [25] performed baseline access flow measurements in 70 patients with grafts and followed the patients prospectively. Among 19 patients with a baseline access flow < 600 ml/min, only 6 (or 32%) of the patients had graft thrombosis in the subsequent 3 months (**Table 5**). Conversely, among 51 patients whose access flow was ≥ 600 ml/min, 10 (or 20%) still experienced graft thrombosis. In other words, using this threshold in these patients would have resulted in unnecessary angioplasty in two-thirds of patients with an abnormal test, while graft thrombosis would have still occurred in a substantial number of patients (with a false negative test).

Dember et al [24] evaluated the performance characteristics of static venous pressure ratio (SVPR) measurements in the clinical management of grafts. They concluded that there was no SVPR ratio that would adequately separate grafts likely to thrombose from those that would remain patent. An SVPR ≥ 0.4 would lead to unnecessary interventions in 53% of patients who would not have thrombosed during the subsequent month, while failing to intervene in 27% of patients destined to have graft thrombosis. If the SVPR threshold was raised to 0.5, the proportion of unnecessary interventions would be reduced to 25%, but 52% of patients destined to have graft thrombosis would not undergo preemptive angioplasty.

Paulson et al performed a meta-analysis of studies evaluating flow monitoring for prediction of graft thrombosis [29]. They plotted receiver operator characteristic (ROC) curves for the published studies, and concluded that the test was not sufficiently accurate to be a clinically useful predictor of graft thrombosis. In summary, improving the performance of any surveillance test would require the ability to identify the subset of stenosed grafts at risk for future thrombosis, so that preemptive angioplasty could be reserved for this high-risk subgroup. Unfortunately, there is currently no noninvasive test to distinguish reliably between these two groups.

Does preemptive angioplasty of graft stenosis detected by surveillance reduce graft thrombosis?

Observational studies

Numerous publications have reported on the frequency of graft thrombosis before and after implementing a comprehensive program of clinical monitoring or surveillance for graft stenosis at a dialysis center [10, 14, 30-33]. Each of these studies initially measured the frequency of graft thrombosis during a baseline “do-nothing” period in which grafts were referred for an intervention only once they clotted. After introducing the monitoring/surveillance program, patients with suspected graft stenosis were referred for a confirmatory angiogram, along with a concurrent angioplasty if 50% stenosis was observed. Each of these studies observed a dramatic decrease (41 to 77%) in the frequency of graft thrombosis during the interventional period as compared with the historical baseline (**Table 6**).

A recent study reported no correlation between static dialysis venous pressures and access flows [34]. This finding suggests that combining surveillance tests looking at access pressure and those measuring access flows may increase the positive predictive value for stenosis, as compared with each test alone. An observational study compared graft outcomes in patients undergoing static dialysis venous pressure monitoring, flow monitoring, or the combination of both surveillance methods [26]. The frequency of preemptive angioplasty and graft thrombosis was similar in all 3 groups, indicating there was no advantage to combining the two surveillance strategies.

Randomized clinical trials

Six randomized clinical trials have evaluated the efficacy of stenosis surveillance with preemptive angioplasty on graft thrombosis and longevity [8, 13, 15-17, 35]. The studies have enrolled between 64 and 189 subjects, with patients being randomized to clinical monitoring alone or to graft surveillance (**Table 7**). The method of stenosis surveillance in the experimental group was static dialysis venous pressure in 1 study, flow monitoring in 2, and Duplex ultrasound in 4. One study had 2 different interventional arms, with one arm using flow monitoring and the other arm using Duplex ultrasound [17]. The frequency of angioplasty in the control group varied considerably in different studies, from a low of 0 to a high of 0.64 per patient-year. This variation likely reflected the consistency of the dialysis staff in performing clinical monitoring. Importantly, the frequency of angioplasty was higher in the interventional group than in the control group in 5 of 5 studies providing this information, suggesting that all 3 methods of surveillance were successful in detecting sub-clinical graft stenosis.

What was the impact of graft surveillance and preemptive angioplasty on the frequency of graft thrombosis in these randomized studies? The frequency of graft thrombosis was comparable in the surveillance and control groups (**Table 7**). Similarly, time to graft thrombosis was not statistically significant between the 2 treatment groups for the 5 studies reporting this outcome. Finally, time to permanent graft failure did not differ between treatment arms in 4 of 5 studies, but was significantly longer in 1 study [35]. A recent meta-analysis of the randomized studies observed no significant decrease in graft thrombosis

between the surveillance group and the control arm (Relative risk, 0.94: 95% confidence interval 0.77 to 1.16)[36]. Similarly, the risk of permanent graft failure was similar between the 2 groups (RR 1.08; 95% CI, 0.83 to 1.40) [36]. This meta-analysis means that, at best, graft surveillance may reduce the risk of graft thrombosis by 23% and the risk of permanent graft failure by 17%.

Why are the randomized studies of graft surveillance negative?

What might account for the negative findings of the randomized trials of graft surveillance, in contrast to the impressive reduction of thrombosis in the observational studies? One possibility is that graft surveillance with preemptive angioplasty is simply not beneficial. Observational studies can only test for associations, but they cannot prove causality. Patients receiving the intervention and those not receiving it are not matched, and may differ from each other in clinical characteristics or practice patterns. These differences, rather than the intervention of interest, may account for the differences in outcomes. In randomized studies, enrolled patients have an equal chance of being assigned to either intervention arm. Thus, the experimental and the control arms should be matched for both measured and unmeasured variables. As a result, a difference in outcomes between the two treatment arms can be attributed to the intervention itself, rather than to other clinical variables. Similar discrepancies between observational and randomized trials have occurred in other interventions in the dialysis population [37]. Thus, whereas several observational studies had observed a striking inverse association between dose of dialysis and patient mortality, a randomized clinical trial found no difference in patient survival between a higher and lower dose of dialysis [38]. Similarly, whereas patient mortality is inversely associated with hemoglobin in observational studies of hemodialysis patients, a randomized clinical trial found no beneficial effect of targeting for a normal hemoglobin [39].

Due to study design and difficulty in enrolling patients into randomized clinical trials, the subjects are often healthier than those included in observational studies [37]. As a consequence, the results may not generalize to an unselected hemodialysis population. For example, the randomized clinical trials of graft surveillance enrolled prevalent patients with grafts of different ages. Only a small proportion of the grafts in these studies were new. In an observational study of 346 upper extremity grafts, 30% clotted within 2 months of their creation [2]. The greatest benefit of graft surveillance and preemptive angioplasty may be in new grafts (< 3 months in age). Thus, Ram et al found that the positive predictive value of access flow for subsequent thrombosis was highly dependent on graft age. Specifically, the likelihood of graft thrombosis within 3 months after an access flow < 500 ml/min was ~50% for 30-day-old grafts, ~35% for 600-day-old grafts, and only ~20% for 900-day-old grafts [28]. A secondary analysis of a negative randomized clinical trial suggested that stenosis surveillance with preemptive angioplasty might improve thrombosis-free graft survival in the subset of grafts that had never undergone a previous intervention [40]. Randomized trials restricted to new grafts may be able to show a beneficial effect of stenosis surveillance. Of course, preemptive angioplasty in these grafts would be particularly challenging, as the initial cannulation typically takes 2-4 weeks, flow monitoring cannot be started until the graft is cannulated, low access blood flows need to be confirmed before referring the patient for a fistulogram, and radiologists are reluctant to perform an angioplasty in grafts < 6

weeks in age. Finally, graft stenosis may progress so rapidly in grafts with early thrombosis, such that there is an insufficient opportunity to detect the stenosis by noninvasive means. Although not specifically addressed in the published studies, this phenomenon may account for the 20-25% false negative rate of graft surveillance [24-26].

Finally, even if stenosis is identified in a timely fashion, and the patient undergoes an expeditious preemptive angioplasty, the beneficial effect of this intervention is short-lived. Two prospective studies used flow monitoring to identify patients with significant graft stenosis. Post-angioplasty access flow measurements had returned to the preangioplasty baseline in 20% of patients after 1 week, and in 40% after 1 month, indicating rapid access restenosis [16, 41]. Another observational study reported an increase in access blood flow from 596 to 922 ml/min immediately after angioplasty. However, the access blood flow decreased to 672 ml/min after 3 months. Twenty percent of the grafts had an access blood flow < 600 ml/min one month following angioplasty [42]. Vascular injury arising from the angioplasty procedure results in accelerated neointimal hyperplasia and contributes to restenosis. As a result, the time to restenosis after angioplasty is significantly shorter than the time to initial stenosis [43]. Deployment of stents at the stenotic site, by providing a rigid scaffold, may prolong graft patency after angioplasty. Three retrospective studies have provided support for this hypothesis [44-46]. An ongoing randomized clinical trial is comparing the primary patency of thrombosed grafts treated with thrombectomy and stent deployment, as compared with thrombectomy and angioplasty (ClinicalTrials.gov registration number NCT00496639).

In summary, stenosis surveillance tests for grafts have several major limitations, including their low positive predictive value for graft thrombosis, as well as the substantial proportion of grafts that clot despite a normal surveillance test. Although observational studies have suggested a beneficial effect of surveillance with preemptive angioplasty on the frequency of graft thrombosis, this benefit has not been demonstrated by the majority (5 of 6) randomized clinical trials. The lack of benefit is likely attributable to rapid restenosis following angioplasty. Given the current state of our knowledge, none of the stenosis surveillance tests can be recommended as tools to reduce graft thrombosis. Future research should focus on interventions that prevent neointimal hyperplasia, and thereby limit the pathogenesis of graft stenosis.

What about stenosis surveillance for fistulas?

In contrast to the wealth of research on surveillance for graft stenosis, relatively little has been published on surveillance for fistulas. Until the last few years, the majority of U.S. hemodialysis patients used grafts, so most of the access research focused on grafts. In addition, the frequency of thrombosis is several-fold lower for fistulas than for grafts [47], such that demonstrating a potential benefit of surveillance on fistula thrombosis is more difficult.

How well do monitoring or surveillance predict fistula stenosis? Clinical monitoring is much less predictive of stenosis in fistulas than in grafts. In a large series of dialysis patients undergoing a fistulogram prompted by an abnormality in clinical monitoring, a significant

stenosis was found in only 39% of 185 fistulas vs 69% of 358 grafts [11]. Similarly, static dialysis venous pressure measurements are much less useful in predicting stenosis in fistulas than in grafts [31]. For this reason, most studies have evaluated the performance of flow monitoring in predicting fistula stenosis. In a randomized, controlled pilot study implementation of flow monitoring doubled the likelihood of detecting stenosis confirmed by angiography, as compared with clinical monitoring alone [48].

Schwarz et al determined that an access flow of 465 ml/min was the optimal threshold for prediction of fistula stenosis. Using this value, they determined a sensitivity of 0.89, and a false positive rate of 0.32 [49]. A similar threshold access flow (500 ml/min) was less predictive of fistula stenosis in a second study, with a sensitivity of 0.76 and a false positive rate of 0.32 [50]. The most optimistic report used a threshold access flow of 750 ml/min. For forearm fistulas the sensitivity was 0.93 and the false positive rate 0.12. For upper arm fistulas, the sensitivity was 0.90 and the false positive rate 0 [51].

As with grafts, the more clinically relevant question is whether stenosis surveillance and preemptive angioplasty decreases fistula thrombosis or prolongs fistula longevity. One observational study documented a non-significant decrease in the frequency of fistula thrombosis from 0.15 to 0.07 events per patient-year after implementation of flow monitoring [32]. In contrast, another observational study reported that stenosis surveillance resulted in a 7-fold increase in the frequency of angioplasty without reducing the thrombosis rate or prolonging fistula survival [52].

To date, only two prospective, controlled trials have evaluated stenosis surveillance in fistulas [53, 54]. One was a nonrandomized single-center study, which allocated 62 patients with fistulas (>80% in the forearm) to quarterly flow monitoring with preemptive angioplasty or to a control group [53]. The frequency of fistula thrombosis was 4-fold lower in the surveillance group than in the control arm (0.074 vs 0.317 events per patient-year), and the intervention group had superior functional fistula patency. A second study, performed by the same group of investigators, used a randomized design to evaluate the same research question in 79 subjects [54]. This study also documented a significantly lower rate of fistula failure in the group undergoing flow monitoring.

Restenosis after angioplasty was a common event in both studies, and many fistulas required repeated angioplasties or surgical revisions to maintain their long-term patency for dialysis. The high restenosis rate after angioplasty is in agreement with a previous study, which observed a lack of increase in access flow rate measured one week post-angioplasty in 20% of fistulas [49]. A retrospective analysis of the data from these 2 prospective studies suggested that surgical repair of fistula stenosis is associated with a lower restenosis rate, as compared with angioplasty [55]. In conclusion, these studies suggest that stenosis surveillance may be useful in improving fistula outcomes. However, confirmatory studies from other medical centers would strengthen such a recommendation.

Summary

This review has summarized the current body of literature on clinical monitoring and surveillance in the detection of graft and fistula stenosis prior to thrombosis. Although non-

randomized studies demonstrated a positive benefit in graft longevity in the detection of graft stenosis, no such benefit was found in 5/6 randomized clinical trials. At this time, regular graft surveillance with flow monitoring, static venous pressures or duplex ultrasound cannot be supported by these data. Although fistula stenosis is less common, preliminary data from one center suggests surveillance may be useful, and requires further study.

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Table 1

Primary graft patency after elective angioplasty

Ref	N procedures	% Primary patency at:	
		3 months	6 months
Beathard, 1992 [56]	536	79	61
Kanterman, 1995 [57]	90	N/A	63
Safa, 1996 [14]	90	70	47
Turmel-Rodrigues, 2000 [58]	98	85	53
Lilly, 2001 [4]	330	71	51
Maya, 2004 [11]	155	79	52

N/A, not available.

Table 2

Primary graft patency after thrombectomy

Ref	N procedures	% Primary patency at:	
		3 months	6 months
Valji, 1991 [59]	121	53	34
Trerotola, 1994 [60]	34	45	19
Beathard, 1994 [61]	55 mech	37	N/A
	48 pharm	46	N/A
Cohen, 1994 [62]	135	33	25
Sands, 1994 [63]	71		11
Beathard, 1995 [64]	425	50	33
Beathard, 1996 [65]	1176	52	39
Trerotola, 1998 [66]	112	40	25
Turmel-Rodrigues, 2000 [58]	58	63	32
Lilly, 2001 [4]	326	30	19

N/A, not available.

Mech, mechanical; pharm, pharmacomechanical.

Table 3

Positive predictive value of monitoring methods for graft stenosis

Surveillance method	N of patients	% Positive predictive value
<i>Clinical monitoring</i>		
Schwab, 1989 [33]	58	86%
Cayco, 1998 [10]	68	93%
Robbin, 1998 [12]	38	89%
Safa, 1996 [14]	106	92%
Maya, 2004 [11]	358	69%
Robbin, 2006 [13]	151	70%
<i>Static venous pressure</i>		
Besarab, 1995 [31]	87	92%
<i>Flow monitoring</i>		
Schwab, 2001 [41]	28	100%
Moist, 2003 [16]	53	87%
<i>Ultrasound</i>		
Robbin, 2006 [13]	122	80%

Table 4

Accuracy of flow monitoring in predicting graft thrombosis within 3 months.

Ref	Qa threshold	Followup	PPV	Sensitivity	FPR
May, 1997 [23]	710	3 months	0.25	0.32	0.24
Wang, 1998 [67]	500	2 months	0.43	0.26	0.08
Paulson, 1999 [29]	600	3 months	0.39	0.22	0.12
McDougal, 2001 [25]	600	3 months	0.32	0.38	0.22

Qa, access blood flow

PPV (positive predictive value): probability that a patient with baseline Qa below the threshold will have graft thrombosis during followup.

Sensitivity: for grafts that clotted during followup, the proportion with a baseline Qa below the threshold.

FPR (False positive rate): for grafts that did not clot during followup, the proportion with a baseline Qa below the threshold.

Table 5

Performance characteristics of flow monitoring for graft thrombosis

Access flow	Thrombosis at 3 mo	No thrombosis	% thrombosis
< 600 ml/min	6	13	6/19 = 31%
600 ml/min	10	41	10/51 = 20%
	Sensitivity = 6/16 = 37.5%	Specificity = 41/54 = 76%	

Adapted from McDougal, 2001 [25]

Table 6

Effect of surveillance on graft thrombosis: Observational studies

Ref	Surv method	Thrombosis rate (per graft-years)		
		Historical control	Surveillance period	Percent reduction
Schwab, 1989 [33]	Dynamic dialysis venous pressure	0.61	0.20	67%
Besarab, 1995 [31]	Static dialysis venous pressure	0.50	0.28	64%
Safa, 1996 [14]	Clin monitoring	0.48	0.17	64%
Allon, 1998 [30]	Clin monitoring	0.70	0.28	60%
Cayco, 1998 [10]	Clinical monitoring	0.49	0.29	41%
McCarley, 2001 [32]	Flow monitoring	0.71	0.16	77%

Table 7

Randomized clinical trials of graft surveillance

Reference	Surv method	# subjects		PTA/yr		Thrombosis/yr	
		con	surv	con	surv	con	surv
Lumsden, 1997 [8]	Doppler US	32	32	0	1.5	0.47	0.51
Ram, 2003 [17]	Access flow	34	32	0.22	0.34	0.68	0.91
	Doppler US		35		0.65		0.51
Moist, 2003 [16]	Access flow	53	59	0.61	0.93	0.41	0.51
Dember, 2004 [15]	Static DVP	32	32	0.04	2.1	1.03	0.89
Malik, 2005 [35]	Doppler US	92	97	N/A	N/A	N/A	N/A
Robbin, 2006 [13]	Doppler US	61	65	0.64	1.06	0.78	0.67

N/A, not available.

Surv, surveillance; PTA, percutaneous transluminal angioplasty; thromb, thrombosis; Cum, cumulative; US, ultrasound; DVP, dialysis venous pressure; con, control.