Assessing Blood Flow Through Vascular Access Grafts

by

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Introduction

Patients receiving hemodialysis for the treatment of end stage renal disease require a patent vascular access to remove waste products and excess fluid. Although the autologous arteriovenous fistula is preferred for angioaccess, the lack of a suitable artery or vein necessitates the use of a vascular substitute (Kherlakian, Roedesheimer, Arbaugh, Newmark, & King, 1986). The bovine carotid heterograft, introduced in 1972, has been successful for the creation of vascular access grafts, however, problems such as frequent clotting, infections, false aneurysms, and technical difficulties arising during implantation still occur (Kaplan et al, 1976). To overcome some of these difficulties, the polytetrafluoroethylene (PTFE) graft was designed. The synthetic material is composed of spindle shaped nodes 20 to 30 microns apart, interconnected with fine fibrils. This porous structure enhances fibrous and collagenous ingrowth, and produces a smooth endothelialized lumenal surface (Rapaport, Noon, & McCollum, 1981). The availability of varying sizes, the ease of handling, and the reduced incidence of infection make the PTFE graft more desirable than the bovine heterograft, although stenosis and thrombosis still occur (LeMaitre, Ackman, O'Regan, LaPlante, & Kaye, 1978).

The expected duration of patency for a vascular access graft is largely determined by the occurrence of thickening

and stenosis of the vein. Collagen collects subendothelially in the arterialized vein, starting a few millimeters to four centimeters distal to the surgical anastomoses (Dienst, Oh, Levin, & Kallioinen, 1983). Blood flow through the access graft decreases over time and may cease entirely when occlusion develops.

Doppler ultrasound was first used in 1971 by Stevenson and Lichti to determine patency of grafts and has continued to be beneficial as a noninvasive instrument for determining blood flow (Bouthier, Levenson, Simon, Bariely, Bourquelot, & Safar, 1983; Levy, Ponsin, Bourquelot, Man, Martineaud, 1983; Rittgers, Garcia-Valdez, McCormick, & Posner, 1986). Various studies have shown that flow rates measured by Doppler ultrasound are not significantly different from rates obtained by electromagnetic flow monitors (Kasulke, Lichti, Kapsch, & Silver, 1982; Levy, Bourquelot, Ponsin, Man, & Martineaud, 1984; Shoor, Fronek, & Bernstein, 1979). Isotopic and dye dilution studies have also been used to test the validity of measurements obtained by Doppler ultrasound (Forsberg, Tylen, Olin, & Lindstedt, 1980; Keen, 1985; O'Regan, LeMaitre, & Kaye, 1978).

Forsberg, Tylen, Olin, and Lindstedt (1980), found accurate measurements performed on a fistula difficult to obtain because of turbulence and errors in the cross-sectional area. The diameter of the graft is known at the time of placement, but this measurement cannot be used for calculation of flow because of the proliferation of the

neointimal layer over time. Accurate measurements of the cross-sectional area of the fistula are difficult to determine.

Keen (1985), however, circumvented the problem of knowing the actual cross-sectional area of the heterologous vascular access graft. Since Doppler voltage signal is directly proportional to linear flow velocity, total graft flow can be calculated by correlating the change in Doppler voltage to the change in graft flow which occurs when there is a stepwise diversion of flow from the central body of the graft to the dialyzer. Total graft flow is determined when the Doppler voltage signal (DVS) equals zero, which occurs when all flow is diverted through the extracorporeal circuit. The regression of DVS on flow rates showed a correlation of r =0.97 with graft flow precision ± 4.3% (Keen, Preisig, & Gotch, 1986).

Routine methods of assessing the adequacy of blood flow through a vascular access graft include feeling the thrill and listening to the bruit with a stethoscope. Due to the variability in size, depth of the vessels, and the amount of subcutaneous tissue, thrills and bruits are not graded (Gould, 1982). The absence of a thrill or bruit on the venous side indicates inadequate flow (Cambell, 1984; Chambers, 1981). Because of the invasiveness and cost, direct measurement of blood flow, done by electromagnetic monitoring or isotopic and dye dilution studies, is often omitted unless a complication arises. With these current

assessment practices, deterioration of access grafts is difficult to monitor.

Utilizing the techniques described by Keen (1985), this study used Doppler ultrasound to quantitate monthly changes in blood flow through PTFE grafts and to evaluate the effect of dialysis on graft flow. Two assumptions were made for the implementation of this study. First, since vascular access grafts are inert conduits with vasoactive segments anastomosed at each end, there is no autonomic control of intragraft cross-sectional area. Second, the cross-sectional area of the central body of the graft does not change when some fraction of graft blood flow is diverted through the dialyzer circuit.

Methods and Materials

This study consisted of 2 phases. During phase 1, in vitro studies, described by Keen (1985), were performed to establish the reliability and validity of the Doppler technique for use in vivo. These studies established the linearity of the mean Doppler voltage output to flow velocity, and determined the effect of probe angle on the linearity of the voltage velocity relationship. Phase 2 consisted of in vivo application of the proposed Doppler technique to quantitatively assess vascular access graft flow in dialysis patients over time.

In Vivo Studies

Nine patients, 2 males, 7 females, aged 42 to 82 years (mean 64 years, SD 10.23), with PTFE grafts in a loop or a straight configuration, were evaluated once a month at the beginning and end of a dialysis treatment for up to seven months for a total of 90 studies. In 10 cases, the second study was not done because of technical or patient complications which prevented restudy. Inclusion criteria included patients with a PTFE graft in the arm or leg, placed at least three months ago, who dialyze two or more times per week. Six of the grafts were located in the forearm, 2 in the upper arm, and 1 in the thigh. Graft age ranged from 3 to 35 months, with a mean of 17.56 months (SD 10.82). Five of the patients had a history of graft malfunction related to clotting. Table 1 summarizes the clinical characteristics of the subjects. Subjects 1, 4, and 12 were eliminated from this study because of complications necessitating graft replacement.

In Vivo Pump Calibration

A predialysis pump calibration with normal saline was performed with the extracorporeal circuit (Fresenius A 200-8C, Bad Homburg, FRG) to be used for the dialysis treatment. The pump speed was set, flow allowed to stabilize for 20 seconds, and a timed collection performed. Collection times were determined to 0.01 seconds using a digital stopwatch. Pump speeds were selected to provide volumetric flows equal to the prescribed blood flow rate and

Table 1. Clinical Characteristics

Subject (n=9)	Age	Sex	Race	Cause of Renal Failure	Location of Graft	Configuration of Graft	Age of Graft (Months)	Previous Declotting
2	68	F	Black	Unknown etiology	Forearm	Straight	21	None
3	68	F	White	Glomerulonephritis	Forearm	Straight	35	1985
5	60	F	Chinese	Unknown etiology	Upper arm	Loop	9	None
6	51	M	Black	Glomerulonephritis	Thigh	Loop	10	1987
7	48	F	Black	Diabetic nephropathy	Upper arm	Loop	16	None
8	70	F	Black	Diabetic nephropathy	Forearm	Loop	9	1987
9	82	F	Chinese	Unknown etiology	Forearm	Loop	3	None
10	66	F	Mexican	Diabetic nephropathy	Forearm	Loop	29	1987
11	63	M	Filipino	Diabetic nephropathy	Forearm	Loop	26	1985
Mean	64						Mean 17.56	
SD	10.23						SD 10.82	

one-half of the prescribed rate, and ranged from 120 to 450 ml/min. A minimum of 2 pump settings were studied with each calibration, and at least 2 timed collections were done at each pump setting. Volumetric flows were calculated for each collection, and a mean flow rate was determined.

In Vivo Doppler Measurement

Hemodialysis was initiated according to standard procedure. Fistula needles (15 gauge) were placed in the vascular access graft at least 2 inches apart. A site between the needles was selected for probe placement and Aquasonic contact gel (Smith, Kline Instruments, Sunnyvale, CA) applied. A 15° flat angle Doppler probe (Parks Electronics, Beaverton, OR) with a nominal frequency of 9.3 mHz was positioned with the piezoelectric crystals oriented toward oncoming flow. While the extracorporeal circuit operated at the prescribed blood flow rate, the probe was adjusted until maximum audio and meter signals were obtained and then secured with tape to prevent movement. The Doppler Model 806A (Parks Electronics, Beaverton, OR), a bi-directional system, converted the Doppler shift to a mean voltage. Output was recorded on the R1-5 D.C.P. Recorder (Parks Electronics, Beaverton, OR).

After securing the probe, the blood pump was stopped. The amount of filtrate removed as indicated by the extracorporeal circuit was noted. Flow through the graft was allowed to stabilize for approximately 20 seconds. A recording was made of the Doppler signal representing total

graft flow. The signal was recorded for at least 15 seconds. Further recordings were made at the pump speeds used for calibration. The probe was then removed and a supine blood pressure obtained. Venous pressures sensed by the extracorporeal circuit and displayed on a linear scale in increments of 20 mmHg were noted. The patients were also studied within 15 minutes of dialysis termination, using the described Doppler protocol.

The Doppler recording was analyzed by division of the recording for a given pump setting into 25 mm increments (equal to 5 seconds) and calculation of a mean voltage for each of these increments for a total of 3 values at each setting. An overall mean voltage for a given pump setting was then determined from these increments. Graft flow was calculated for each Doppler study from the linear regression as follows

$$v = a - b(QB)$$

Where v is the Doppler voltage; a is the intercept; b is the slope; and QB is blood flow rate through the extracorporeal circuit. When voltage equals zero, which means that total graft flow is diverted through the extracorporeal circuit, QB = QG

$$0 = a - b(QB)$$

Therefore

$$QB = \frac{a}{b} = QG$$

The month to month variability of QG was determined by averaging the percent difference of the beginning dialysis flow rates (QG_b) from the mean QG_b.

An indirect measurement of mean arterial pressure was obtained using the following equation

$$MAP = \frac{1}{3}(SP - DP) + DP$$

Where MAP is the mean arterial pressure; SP is the systolic pressure; and DP is the diastolic pressure (Cohn, 1985).

Venous pressure (PVEN), measured by a sensor in the air bubble trap of the dialyzer, refers to pressure between the air trap and the return access site. A transducer converts a pressure signal to an electrical signal and displays it on the meter (Keshaviah, & Shaldon, 1983). Because of the variability in pump settings, PVEN was analyzed as a function of the blood pump speed (QB). One-way analysis of variance tests were performed to determine differences between subjects.

The amount of filtrate removed (QFT), as computed by the dialyzer, was normalized among all subjects using the urea kinetic model described by Gotch (1986). The subject's ideal body weight was calculated by the equation

$$IBW = \frac{V}{0.58}$$

Where IBW is the ideal body weight, V is the individual subject's body weight determined from end-dialysis blood urea nitrogen (BUN)/ predialysis BUN and the product of urea clearance and dialysis time. The values for V in this study

were determined by blood tests done within ten days of the Doppler study. The IBW was then used to normalize QFT as shown by the equation

$$\text{Normalized QFT} = \text{QFT} \cdot \frac{\text{IBW}}{\text{DBW}}$$

Where QFT is the amount of filtrate removed at the time of the end-dialysis Doppler study; IBW is the ideal body weight determined by the previous equation; and DBW is the dry body weight obtained postdialysis. Normalized QFT values were analyzed using one-way analysis of variance tests.

Results

After completion of the study, the subjects were divided into three groups based on graft flow rates. QG of Group 1 ranged from 252 ml/min to 838 ml/min (mean 443.57 ml/min, SD 133.24). QG range of Group 2 was 438 ml/min to 1641 ml/min (mean 702.35 ml/min, SD 246.55). The range of QG for Group 3 was 774 ml/min to 3681 ml/min (mean 1846.84 ml/min, SD 684.92). Monthly measurements of QG varied by 17 ± 10% in Group 1, 24 ± 19% in Group 2, and 16 ± 16% in Group 3, with no consistent pattern. Figure 1 displays the flow rates at the beginning of dialysis (QG_b) of all subjects.

The mean change in QG from the beginning of dialysis to the end was 15 ± 6% for Group 1, 23 ± 8% for Group 2, and 44 ± 30% for Group 3. No significant differences between the groups were found.

Mean arterial pressures of all subjects ranged from 69 mmHg to 117 mmHg (mean 94.94 mmHg, SD 4.90). The change in

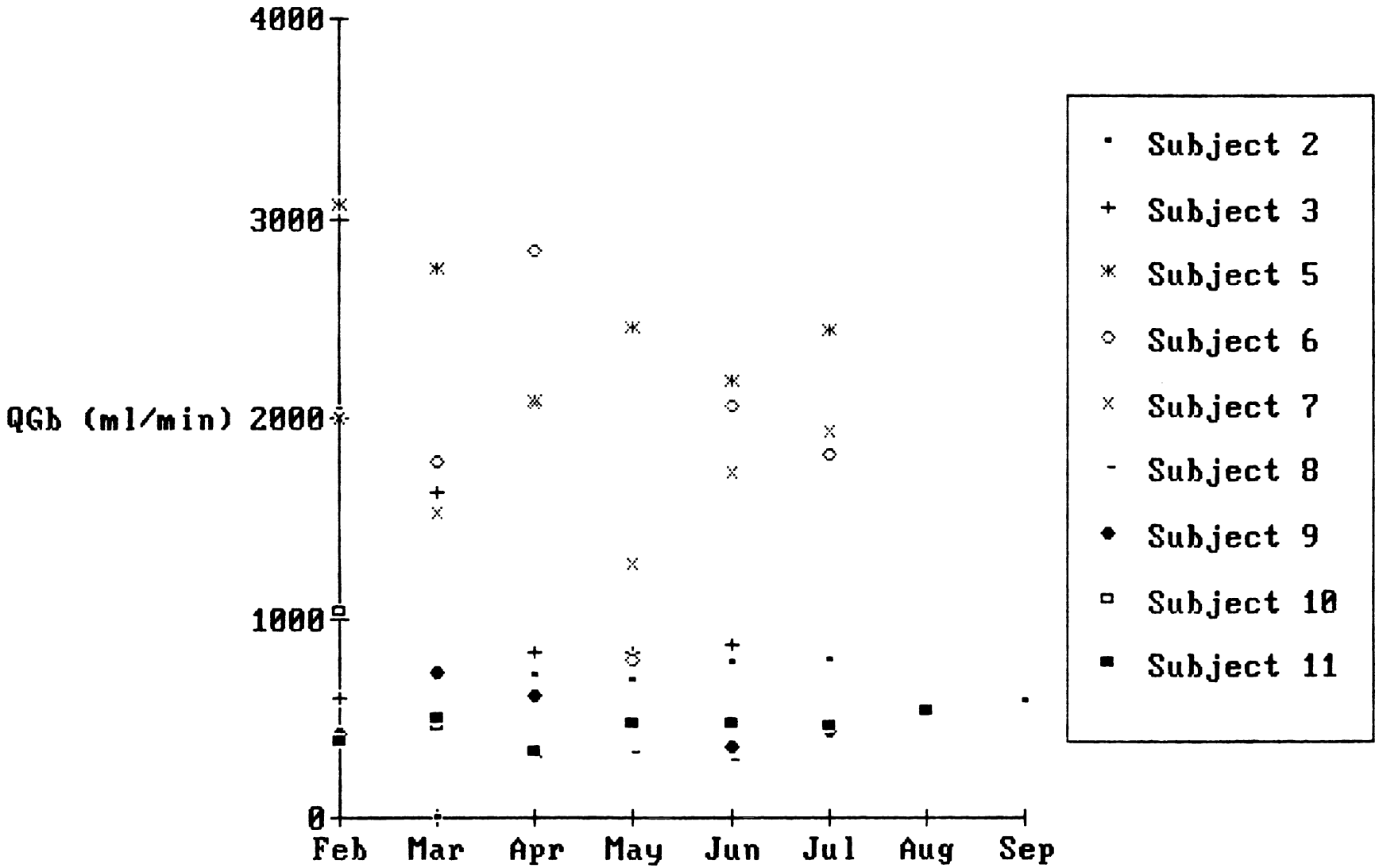

Figure 1. Summary of flow rates at the beginning of dialysis

MAP from the beginning of dialysis to the end ranged from -20 mmHg to 21 mmHg (mean 1.93 mmHg, SD 11.26). No significant differences between the three groups were noted. No relationship was found between MAP and normalized QFT or the change in MAP and the percent change in QG (QG_e/QG_b) as shown by Figures 2 and 3.

Mean venous pressures (PVEN), measured by the extracorporeal circuit were 162 mmHg (SD 42.12) in Group 1, 199 mmHg (SD 48.01) in Group 2, and 241 mmHg (SD 28.67) in Group 3. These values are significantly different (F ratio = 14.03, P <0.003). When PVEN was analyzed as function of blood pump speed (QB), there was no significant difference between the three groups. The mean corrected venous pressure ($PVEN_c$) was 0.66 ± 0.13 mmHg in Group 1, 1.56 ± 0.11 mmHg in Group 2, and 0.59 ± 0.11 mmHg in Group 3. Despite a 15% to 44% decrease in QG at the end of dialysis, changes in $PVEN_c$ showed no consistent pattern as shown in Figure 4.

The amount of filtrate removed during dialysis ranged from 0 to 4260 ml (mean 2580.71 ml, SD 998.15), with no significant differences between the groups. When these values were normalized by body weight, the range was 892 ml to 3895 ml (mean 2474.40 ml, SD 1059.16) for Group 1 0 to 2702 ml (mean 1292.39 ml, SD 645.64) for Group 2, and 1910 ml to 3786 ml (mean 2572.95 ml, SD 567.24) for Group 3. Group 2 was significantly different from Group 1 (F ratio = 12.47, P <0.002) and from Group 3 (F ratio = 28.39,

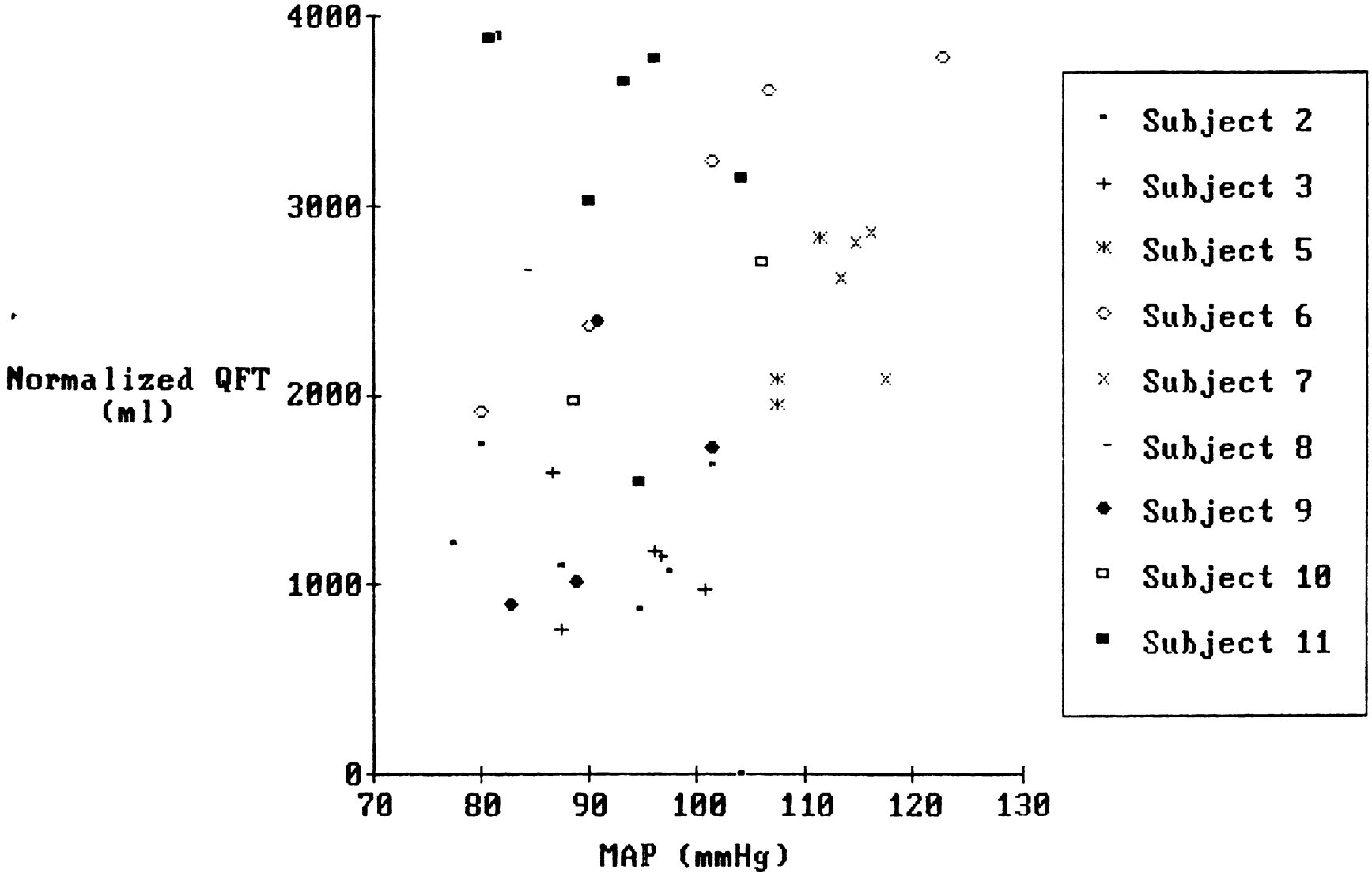

Figure 2. Mean arterial pressure compared with the normalized filtrate removed by the end dialysis Doppler study.

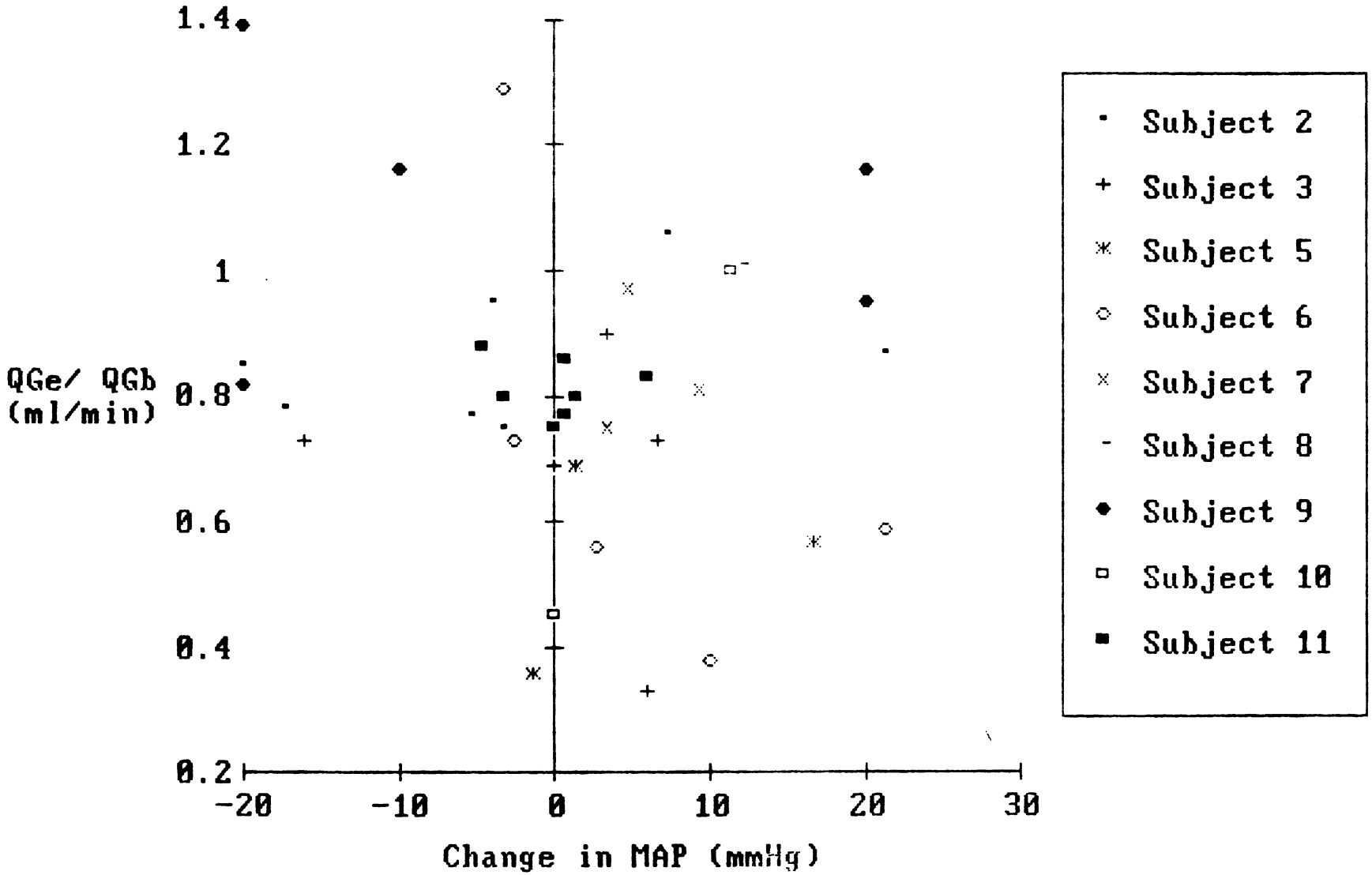

Figure 3. A comparison of the change in mean arterial pressure from the beginning Doppler study to the end, with the percent change in graft flow rates.

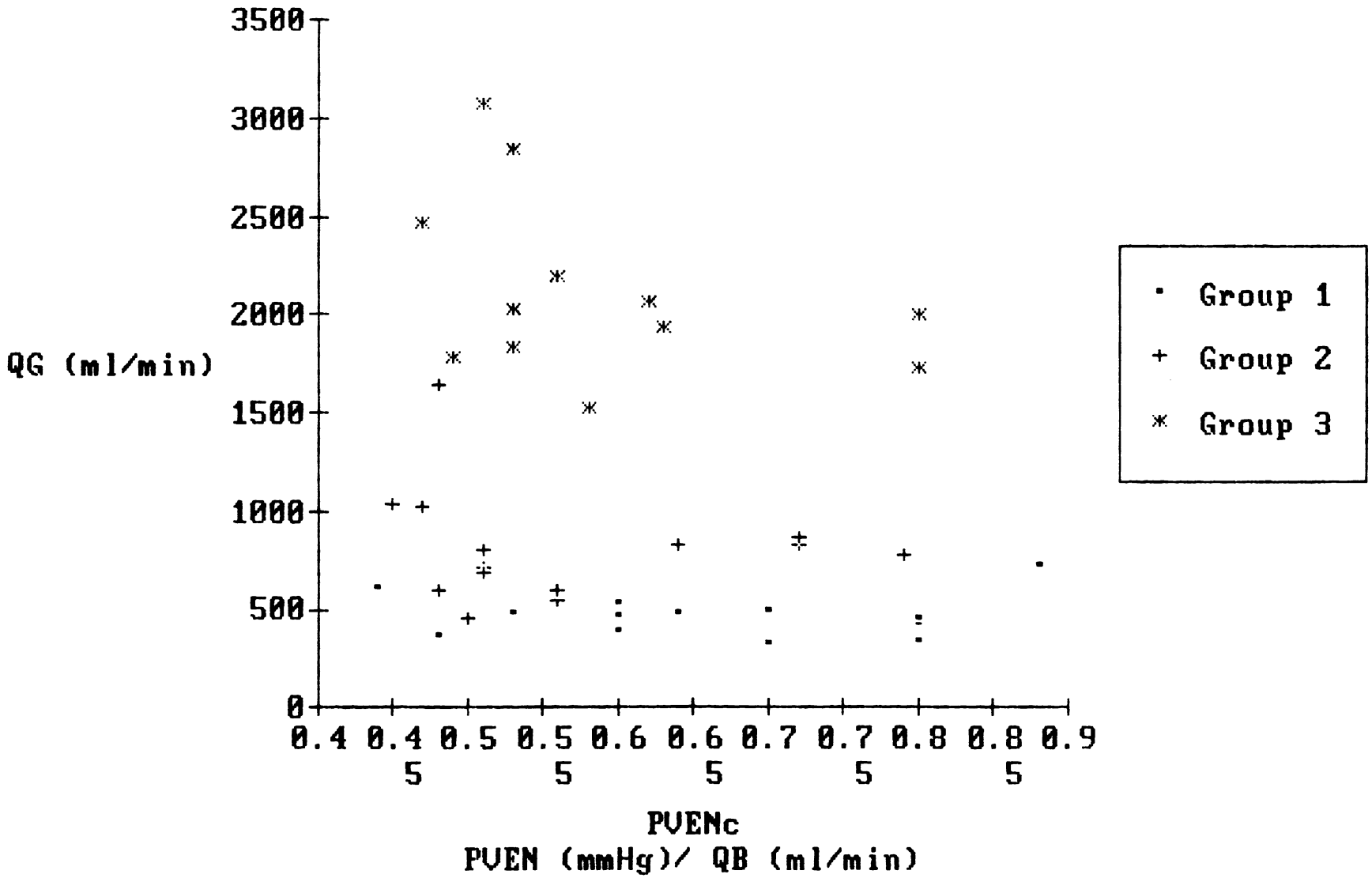

Figure 4. Venous pressure corrected by blood pump speed compared with graft flow rates.

P <0.0002). No significant differences were found between Groups 1 and 3. Neither the percent nor the absolute change in QG correlated with normalized QFT as shown by Figures 5 and 6.

During the time of the study two of the grafts failed. Subject 10 showed a 56% decrease in QG_b, from 1042 ml/min to 459 ml/min, over one month and presented with an occluded graft one week following the second study. PVEN increased slightly from 180 mmHg to 200 mmHg ($PVEN_c$ values 0.45; 0.50). Normalized QFT values changed from 2702 ml to 1962 ml. Declotting of the graft was unsuccessful and a new graft was placed.

Subject 11 presented with an occluded graft during the fifth month of the study, four days prior to the sixth study, and the graft was successfully declotted. QG_b varied 12% (SD 8.8) during the entire study, with no change in QG_b between the fourth and fifth studies (474 ml/min; 478 ml/min). PVEN decreased slightly from 180 mmHg to 160 mmHg ($PVEN_c$ values 0.60 mmHg; 0.53 mmHg). Normalized QFT values increased from 1535 ml to 3787 ml between the fourth and fifth studies. However, normalized QFT values prior to the fourth study ranged from 3021 ml to 3895 ml (mean 3600, SD 501.83). Following declotting QG_b did not change significantly (478 ml/min to 462 ml/min). PVEN increased from 160 mmHg to 240 mmHg ($PVEN_c$ values 0.53; 0.08), but dropped to 180 mmHg (PVENc value 0.60) during the seventh

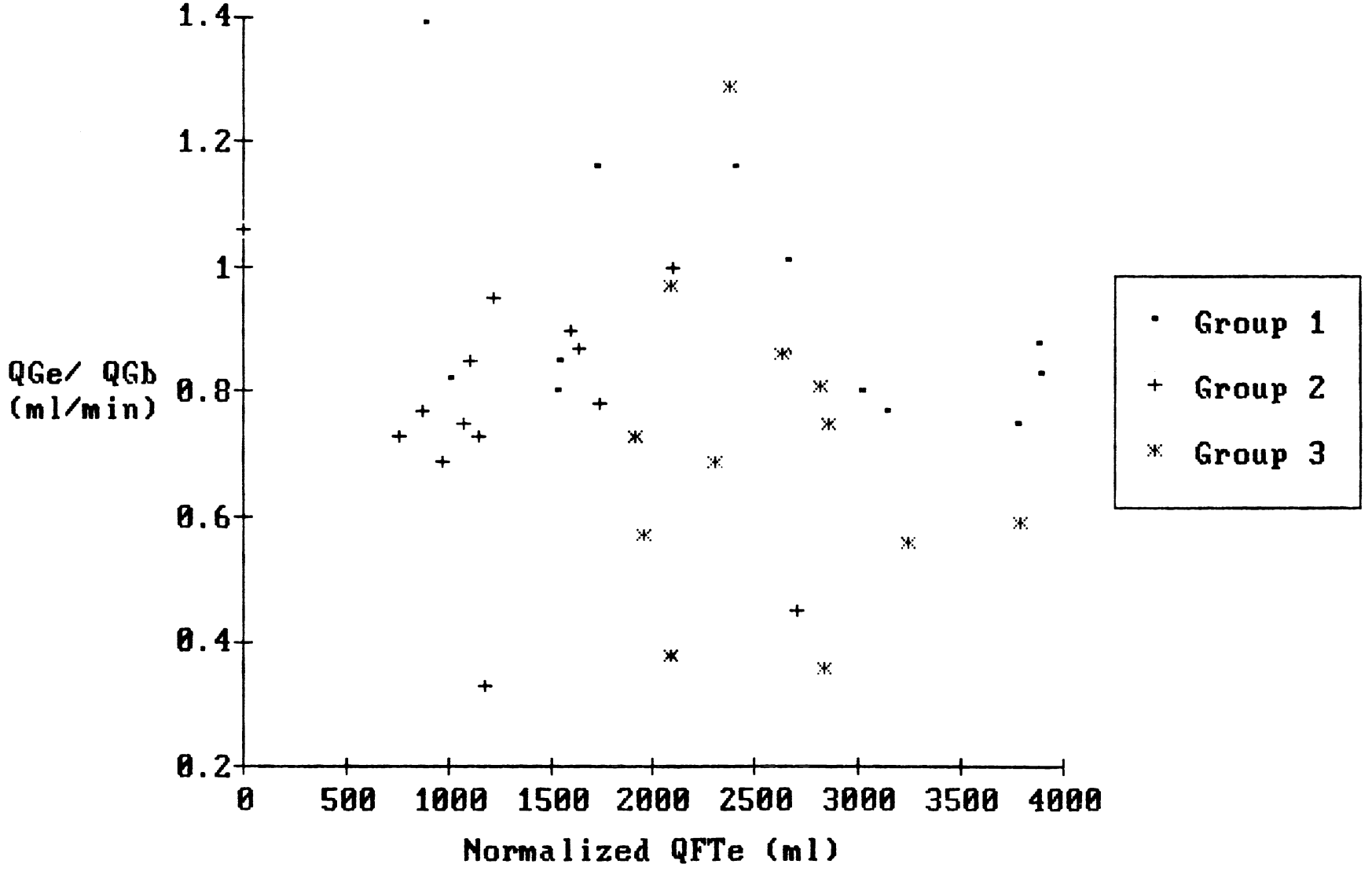

Figure 5. Normalized filtrate removed by the end dialysis Doppler study compared with the percent change in graft flow rates.

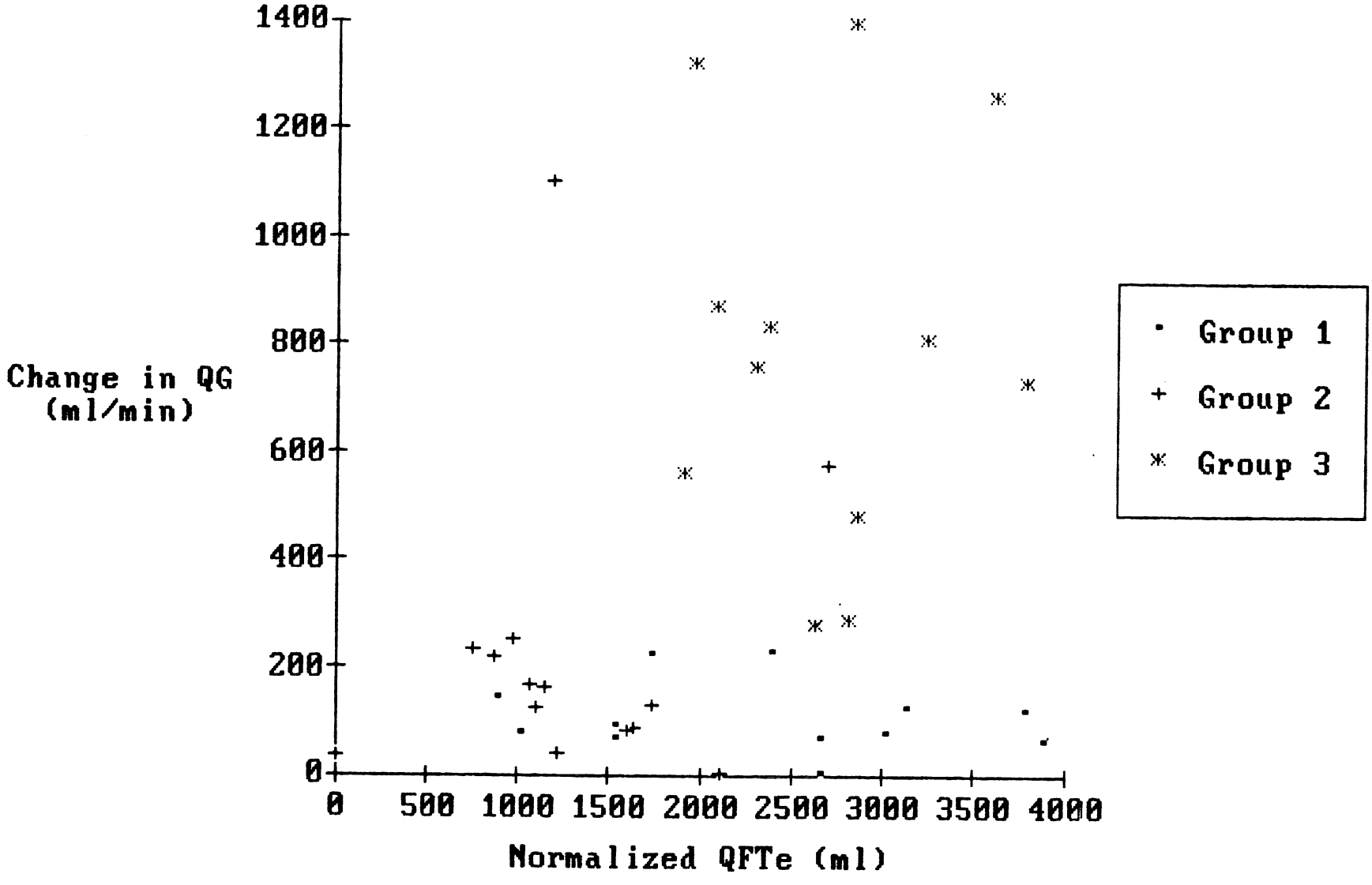

Figure 6. Normalized filtrate removed by the end dialysis Doppler study compared with the absolute change in graft flow rates.

study. Normalized QFT for the sixth study was 3123 ml. Table 2 summarizes these findings.

Discussion

Routine methods of assessing the adequacy of blood flow through vascular access grafts include feeling the thrill, listening to the bruit with a stethoscope, and noting the ease by which dialysis can be performed. These practices provide limited information regarding graft status over time. Using Doppler ultrasound, a noninvasive instrument, monthly changes in graft flow were determined and the effect of dialysis on graft flow was evaluated.

Flow rates in Group 1 and Group 2 determined by this study ranged from 252 ml/min to 1641 ml/min, and are consistent with findings reported by other investigators using Doppler ultrasound to measure blood flow through PTFE grafts (Forsberg, 1980; Forsberg, Holmin, & Lindstedt, 1981; Keen 1985; Rittgers, Garcia-Valdez, McCormick, & Posner, 1986; Rodriguez-Moran, Rodrigues, Boyero, Enriquez, & Morin, 1985).

Although Doppler studies do not document QG in the 2000 ml/min to 3700 ml/min range found in Group 3, these results are similar to flow rates obtained by a constant infusion method with pertechnetate ^{99m}TC injection (O'Regan, LeMaitre, & Kaye, 1978). Rittgers, Garcia-Valdez, McCormick, & Posner (1986) included patients with upper arm accesses and found flow rates to be 1196 ± 376 ml/min when

Table 2. Summary of subjects' studies

Study	Month	QG_b (ml/min)	QG_e (ml/min)	Normalized QFT (ml)	PVEN (mmHg)	$PVEN_c$ (mmHg)
Subject 10						
1	APR	1042	468	2702	180	0.45
2	MAY	459	458	1962	200	0.50
Subject 11						
1	APR	390	322	3895	120	0.60
2	MAY	500	438	3885	140	0.70
3	JUN	332	252	3021	140	0.70
4	JUL	474	381	1535	180	0.60
5	AUG	478	356	3782	160	0.53
6	SEP	462	395	2657	240	0.80
7	OCT	538	413	3142	180	0.60

the graft was anastomosed to the proximal brachial artery. No Doppler studies in the literature include patients with thigh grafts.

O'Regan, LeMaitre, & Kaye (1978) found grafts with flow rates less than 500 ml/min at risk for occlusion. Riggers et al (1986) noted that grafts with flow less than 450 ml/min occluded within two weeks. The findings of this study, however, do not support the relationship between low flow and loss of patency. Grafts with flow rates of 300 ml/min to 400 ml/min over a period of 6 months did not occlude.

A 16% to 24% variability in monthly measurements was found in grafts with low, medium, and high flow rates, with no evidence of access deterioration. Similar findings of variability are summarized in the study performed by Rittgers et al (1986), although not analyzed. The 56% decrease in QG_b which preceded occlusion in Subject 10 suggests that large percent decreases may signal graft failure. Serial Doppler evaluations need to be performed to determine the flow rate range defining adequate function for individual patients.

Recirculation, the mixing of outflow blood with inflow blood, is caused by dialysis needles placed too closely or a fistula with low flow, either through the outflow vein or within the body of the graft. Associated symptoms include an increase in drip chamber pressure or decreased clearance of metabolic waste products (Gutch, & Stoner, 1983). Using

the Doppler technique described by Keen (1985), recirculation is manifested by an increase in Doppler voltage directly proportional to the amount of blood diverted through the extracorporeal circuit. Despite a 15% to 44% reduction in QG from the beginning of dialysis to the end, none of the subjects showed evidence of recirculation, suggesting that dialysis efficiency was not compromised.

In the majority of patients, fluid removal results in a decrease in arterial blood pressure indicating that the hypertension associated with end stage renal disease is mainly volume dependent (Batlle, 1981). A drop in plasma osmolality, caused by the removal of blood urea nitrogen and other osmotic agents may also contribute to a lower pressure (Henrich et al, 1980). Batlle, von Riotte, and Lang (1986) demonstrated that blood pressure falls markedly after dialysis, especially during the fifth hour postdialysis, rather than during the procedure. Their data suggest that the hypotensive effect of fluid removal is balanced by vasopressor agents such as Angiotensin II, catecholamines, and arginine vasopressin. The findings of the present study support the research findings of Batlle, von Riotte, and Lang (1986). A decrease in QG did not result in a subsequent fall in MAP. No relationship exists between the change in MAP and the amount of filtrate removed. Therefore, one cannot predict which patient will become hypotensive during a dialysis treatment based in the amount of fluid to be removed.

The results of this study also indicate that graft flow is unaffected by the amount of filtrate removed. This finding becomes beneficial when caring for the fluid overloaded patient. If QG is within the patient's adequate range, then large amounts of fluid can be removed without fear of compromising dialysis efficiency.

Elevated venous pressures may indicate a kinked line, a clotted air trap, or a malaligned venous needle (Gutch, & Stoner, 1983). Venous pressures may also rise if the venous needle gauge is too small to allow adequate return of flow in relation to the blood pump speed. Consistently high pressure readings suggest stenosis (Wing, & Magowan, 1975). Low venous pressures signal a decrease in flow caused by a malaligned arterial needle, low systemic blood pressure or, on rare occasions, arterial stenosis (O'Regan, LeMaitre, & Kaye, 1978).

In this study, PVEN, even when corrected for blood pump speed ($PVEN_C$), is not indicative of graft flow. In the two cases of graft occlusion, PVEN did not rise significantly. In one subject, PVEN increased slightly from 180 mmHg to 200 mmHg, and decreased from 180 mmHg to 160 mmHg in the other. These data suggest that patients with low or normal PVEN have the same risk for occlusion as patients with elevated PVEN.

Recommendations for future studies include monitoring graft flow each dialysis visit for two weeks to determine individual variability. Subsequent studies can then be done

biweekly. Grafts with flow rates outside the individual range should be assessed more frequently. If flow rates remain outside the normal range, then interventions to salvage the graft can be initiated prior to occlusion.

With the advent of synthetic erythropoietin, further research also needs to be done to determine if changes in blood viscosity significantly affect blood flow through vascular access grafts.

In summary, this Doppler procedure is useful in determining graft flow by a noninvasive method without knowing the internal diameter of the vascular access graft, alerting health care providers of grafts with low flow that may be inadequate for high flux therapy, and detecting graft recirculation.

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