AN ORIGINAL METHOD TO EVALUATE VASCULAR ACCESS FLOW IN DIALYSIS PATIENTS

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Abstract: The on-line monitoring of vascular access flow (*Qa*) during hemodialysis treatment is considered useful to allow the early detection of stenosis evolving. We suggest a new method to predict *Qa* using informations usually available during the treatment without the necessity of supplementary devices. During each study session, patient access flow (Qa_{Trans}) was measured with Transonic® according to the Krivitsky method. Moreover, the pressure in the arterial (P_{af}) and venous (P_{vf}) puncture site of the arterio-venous fistula were evaluated at different values of blood flow (Qb_{real}). Finally, the fistula pressure gradient ($P_f = P_{af} - P_{vf}$) was analysed as a function of the correspondent values of Qb_{real}. We supposed that Qa_{Inv}, defined as the value of Qb_{real} at which *Pf* becomes negative, is related to the fistula hemodynamics in such a way that it can provide information on *Qa*. The Qa_{Trans} (778±441 ml/min, N=18) and the Qa_{Inv} (208±88 ml/min) highlighted a good correlation (R^2=0.68). Then, the access flow evaluated (Qa_{Ev}) with regression line (Qa_{Ev}=4.35*Qa_{Inv}-138.34) was 778±390 ml/min, with a mean prediction error of 0±34%. Our method of access flow estimation highlighted a good prediction capability of the vascular access flow measured with Krivitsky method.

Introduction

Vascular access is usually considered as one of the most critical aspects of the hemodialysis treatment. Actually, vascular access failure represents a major cause of morbidity and hospitalisation for dialysis patients with a high cost impact on the public health [1]. The intra-dialytic monitoring of vascular access flow (*Qa*) is considered a practice useful to allow the early detection of stenosis evolving [2]. This monitoring is usually done by means of procedures that require expensive and time-consuming methods and equipments. We suggest a new method to predict access flow using information usually available during the treatment. To predict the value of Q_a, we used the difference of pressures between the arterial (P_{af}) and venous (P_{vf}) access points, evaluated at different blood pump flow in the extracorporeal circulation (*Qb*). Hereafter an in-vivo validation test is presented.

Materials and Methods

All patients considered in the study were enrolled from S. Carlo Clinic (Paderno Dugnano, Italy) and were treated with Integra® dialysis machine (Gambro Dasco, Medolla, Italy).

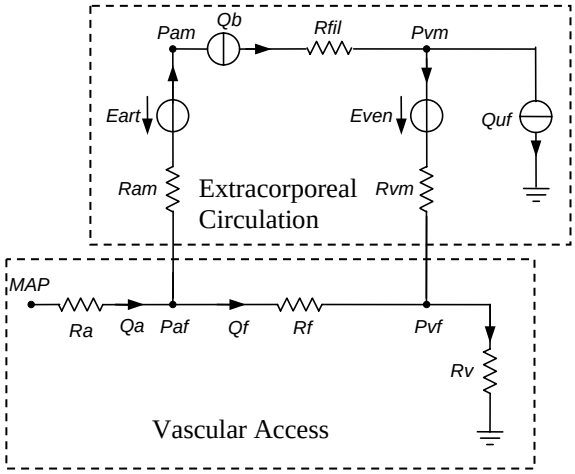

Figure 1: Model of pressure drop along the extracorporeal circulation of a hemodialysis machine and in the vascular access of the patient. Symbols: MAP mean arterial pressure, R_a R_f R_v hydraulic resistances of vascular access, R_{am} R_{vm} R_{fil} hydraulic resistances of extra-corporeal blood lines and filter, E_{art} E_{ven} static pressures due to heights differences between drip chambers and needles, P_{af} P_{vf} pressure in the arterial and venous puncture site of arterio-venous fistula, P_{am} P_{vm} pressure in the arterial and venous drip chamber, *Qa Qb Quf Qf* blood flows in the fistula, in the blood line, ultrafiltration rate and blood flow between the arterial and venous puncture site.

The inclusion criteria were: i) patients with chronic renal failure on hemodialysis therapy, treated for at least 3 months (stabilized patients); ii) age > 18 years; iii) proximal native artero-venous fistula, punctures along

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the same vessel, with arterial needle in counter-current and venous in co-current with blood flow. The evaluation of patient access flow was based on a hydraulic model (Fig. 1), previously developed [4], of the pressure drop along extracorporeal blood lines and in the arterio-venous fistula (AVF). In particular, the pressure in the arterial (P_{af}) and venous (P_{vf}) access points were evaluated starting from the values of pressure in the respective drip chambers P_{am} and P_{vm} as following:

$$P_{af} = P_{am} + R_{am} \cdot Q_b - E_{art} \quad (1)$$

$$P_{vf} = P_{vm} - R_{vm} \cdot \left(Q_b - Q_{uf}\right) - E_{ven} \quad (2)$$

where E_{art} E_{ven} are the static pressures (in mmHg) due to height differences between the drip chambers and the needles. The values of the static pressures were evaluated as following:

$$E_{ven} = 0.77 \cdot \Delta H_{ven} \quad (3)$$

$$E_{art} = 0.77 \cdot \Delta H_{art} \quad (4)$$

where ΔH_{ven} and ΔH_{art} are the difference of height (in cm) between the blood level in the venous and arterial drip chambers and the corresponding puncture site. Moreover R_{am} R_{vm} are hydraulic resistances of extra-corporeal blood lines. These resistances were evaluated as function of *Qb* and blood hematocrit (*Hct*). The dependence of R_{am} and R_{vm} from *Qb* and *Hct* was determined during an in-vitro study previously carried out. An accurate measurement of the pressures P_{am} and P_{vm} at the drip chambers needs the removal of the periodic oscillation induced by the blood pump rotation. This oscillation has a null average value in a interval equal to the pump rotation period. Consequently, to remove the oscillation, P_{vm} and P_{am} were measured as a time-average done on the three pump rotation periods, detected thanks to a infrared light sensor screwed to blood pump cover. During each session, the effective blood pump flow (Qb_{real}) was continuously monitored by means of Transonic® Hemodialysis Monitor (HD01^{plus} by Transonic Systems Inc., Ithaca, NY, USA). A dedicated box, battery powered, was assembled to acquire P_{am}, P_{vm}, Qb_{real} and pump rotation period. The box also includes two pressure transducers (SCX15DN by SenSym ICT^{TM}) and the conditioning electronics for pressure transducers. Two additional disposable lines allow the connection between arterial and venous drip chambers to the dedicated sensors. A laptop equipped with a National Instrument^{TM} acquisition board (NI DAQ 6062E) with a dedicated software package for data acquisition and elaboration, developed with LabView^{TM} was used. This software package controls the acquisition, stores data into an Access^{TM} database and guides the user to perform the operations during the test. For each session the time-average pressures P_{am} and P_{vm} were measured at the following values of blood flow setting (Qb_{set}): 250, 50, 0, 50, 100, 150, 200, 250, 300, 350 ml/min. Moreover, systemic arterial pressure, heart rate, hematocrit level in the arterial and venous blood line were measured before and after the registration session. For each session considered in the present study, the fistula pressure gradient (P_f), defined as:

$$P_f = P_{af} - P_{vf} \quad (5)$$

extracted from the correspondent value of P_{am} and P_{vm}, following the equations (1) and (2), was measured for the different Qb_{set} imposed and analysed as a function of the correspondent averaged values of Qb_{real}. This procedure has to be done to find the value of Qb_{real} at which the P_f is equal to zero. In fact, using the hydraulic model (see Fig. 1) the gradient of pressure in the vascular access (P_f) can be also defined as:

$$P_f = R_f \cdot \left(Q_a - Q_b\right) \quad (6)$$

where R_f is hydraulic resistances of vascular access, different from zero. Consequently, in a theoretical way, the value of Qb_{real} at which the P_f is equal to zero should be equal to the access flow of the patient (*Qa*). Our estimation of the access flow was compared with the method nowadays considered the international gold standard. Therefore, the access flow (Qa_{Trans}) and recirculation ratio were evaluated with Transonic® according to the Krivitsky method [3].

Results

Following the inclusion criteria one session for 10 patients and 2 sessions for 4 patients were collected. The experimental trend of P_f was positive for low Qb_{set} values but became negative for high Qb_{set} values. We defined the value of Qb_{real} at which P_f becomes negative as Qa_{Inv} (Fig. 2). The values of Qa_{Inv} was evaluated algebraically using a second order polynomial function to approximate the dependence of P_f on Qb_{real}.

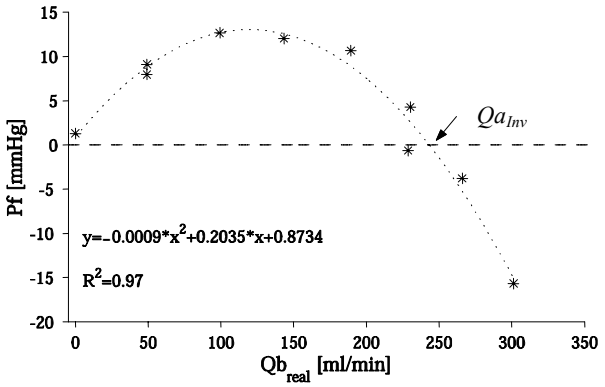

Figure 2: Example of Qa_{Inv} evaluation. Qa_{Inv} is the value of Qb_{real} for which P_f (*) approximated with a quadratic regression (dotted line) equation is equal to zero.

The average value of Qa_{Inv} computed was 210±89 ml/min and the average Qa_{Trans} measured in the patients was 778±471ml/min, with a minimum flow of 115

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ml/min and maximum of 1520 ml/min. Only one patient presented access recirculation (30%). The linear regression between Qa_{Trans} and Qa_{Inv} (Qa_{Inv}=0.1575*Qb_{Trans}+88.085) presented a good correlation (R^2=0.68) as shown in Fig. 3. Then, the access flow evaluated (Qa_{Ev}) using the regression line, shown in Fig. 3, was 778±390 ml/min, with an average prediction error of 0±264 ml/min (i.e. 0±34% of Qa_{Trans}). The values of access flow (Qa_{Trans}) measured with Transonic®, Qa_{Inv}, Qa_{Ev} and the estimation error (Qa_{Ev}-Qa_{Trans}) for all patients are reported in Tab. 1.

Tab 1. Access flow (Qa_{Trans}) measured with Transonic®, Qa_{Inv}, access flow evaluated Qa_{Ev} and the correspondent estimation error (Qa_{Ev}-Qa_{Trans}) for all patients.

	Qa_{Trans} [ml/min]	Qa_{Inv} [ml/min]	Qa_{Ev} [ml/min]	Error [ml/min]
Paz1	500	177.8	635.3	135.3
Paz1	235	240.2	906.8	671.8
Paz2	305	62.7	134.5	-170.5
Paz3	480	209.6	773.6	293.6
Paz3	450	111.5	346.8	-103.2
Paz4	990	243.3	920.3	-69.7
Paz5	280	184.9	666.2	386.2
Paz5	115	7.5	-105.7	-220.7
Paz6	840	236.9	892.4	52.4
Paz7	1030	230.6	865.0	-165.0
Paz7	990	214.3	794.1	-195.9
Paz8	360	111.4	346.4	-13.6
Paz9	1250	277.2	1067.8	-182.2
Paz10	1130	275.5	1060.4	-69.6
Paz11	550	235.4	885.9	335.9
Paz12	1500	329.5	1295.3	-204.7
Paz13	1520	345.0	1362.8	-157.2
Paz14	1480	297.8	1157.4	-322.6

Discussion

The maintenance of the hemodialysis vascular access is now one of the hot research topic in the hemodialysis, after a decade in which research improvements focused on the therapeutic side, disregarding the fundamental role of the vascular access. In particular, in line with recent studies [2, 6] on vascular access monitoring, we suggest an on-line method to evaluate patient access flow, using informations usually available during the treatment without the necessity of supplementary devices. Using on a simple hydraulic model of the extracorporeal circuit, we estimated the pressure gradient (P_f=P_{af}-P_{vf}) between arterial (P_{af}) and venous (P_{vf}) puncture site. P_f was measured for different value of flow (Qb_{real}) in the extracorporeal circuit, in order to evaluate the value of Qb_{real} at which Pf is equal to zero (Qa_{Inv}). As shown in the eq. (6), in a theoretical way, the value of Qa_{Inv} should be equal to the access flow of the patient (Qa).

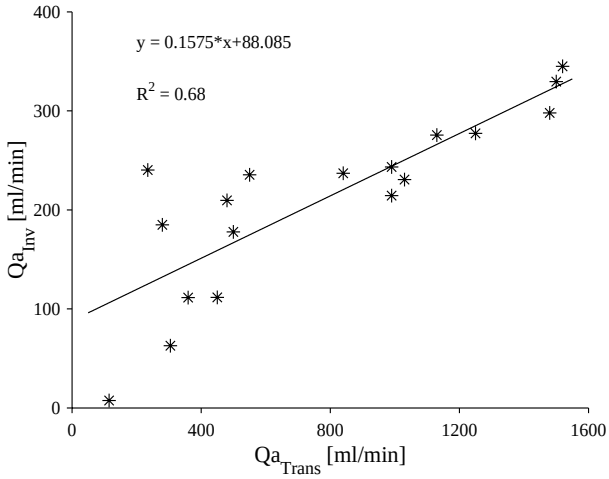

Figure 3: Qa_{Inv} (*) as a function of Qa_{Trans} evaluated in all patient included in the study and the linear regression line (-).

For all the patient included in the study, the evaluated values of Qa_{Inv} were underestimated respect the related values of Qa_{Trans} measured in with Transonic™, but a good correlation (R^2=0.68) was found between Qa_{Inv} and Qa_{Trans}. The underestimation of Qa_{Inv} was caused by low value P_f that becomes even negative for the high blood flow. This effect depends on the high venous pressure (P_{vf}) and low arterial pressure (P_{af}) measured during all the sessions that, as shown in eq. (5), involve a P_f decrease. The variations of P_{vf} and P_{af} are related to the hemodynamics interaction between the flows along the arterial and venous needle and the patient access flow. In particular, the most the access flow is high the less the pressure variations near to the puncture sites are evident, thus increasing the value of P_f and consequently that of Qa_{Inv}. In this way, the Qa_{Inv} is related with AVF hemodynamics and it can provide information on patient access flow. In particular, a good prediction capability was highlighted for the values of access flow higher than 800 ml/min. However, for the access flow less than 400 ml/min, the dispersion of the Qa_{Inv} evaluated respect the Qa_{Trans} increased (see Fig. 3). The cause of this dispersion could be find in the critical characteristics of this class of patient linked to recirculation and to their critic access flow. We believe that taking into account, by means of corrective factors of Qa_{Inv} estimation, characteristics of patients as AVF diameter and length between the two needles, the

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prediction ability could be improved also for low flows. Consequently, future experimental studies focused on critical patients with low flow and stenoses, will be carried on in order to assess this type of corrections of Qa_{Inv} estimation.

In the present study, a dedicated hardware and software were used to measure the pressure in the drip chambers. Nevertheless, we believe that our method could be easily performed using the pressure transducers usually on board of the hemodialysis machine after an hardware and software upgrade. In this way, this procedure for Qa_{Inv} evaluation could be done in an automatic way without the aid of clinicians. On the contrary, the current standard methods of access flow assessment, as color doppler ultrasound analysis [6], ultrasound dilution [3], thermodilution [7], direct transcutaneous optodilution [8] and variable flow doppler [9], use expensive external devices and imply clinicians time consuming. Consequently, the possibility of an automatic implementation of our access monitoring method, could allow frequent access flow measurements, considering the low time consuming for the clinicians. In fact, NKF-K/DOQI guidelines [10] suggest the patient access flow has to be monthly monitored, since a decrease of more than 25% respect to the baseline value is considered to predicting of access failure.

According to Besarab [11], vascular access failure can also be discriminated by the access pressures measured directly at zero blood flow. Moreover, in line with this hypothesis, Kleinekofort [12] introduced the ratio between the pressure in the arterial (P_{af}/MAP) and venous (P_{vf}/MAP) puncture site and the mean arterial pressure (MAP) as a factor that can evaluate access failure and detect the position of stenoses. Our method, in order to evaluated the patient access flow, extracts all pressure informations necessary to assess the failure indexes highlighted by Besarab [11] and Kleinekofort [12]. Therefore, the method we developed allows both the monitoring of the access pressures and the prediction of blood flow, thus creating a complete clinical picture of patient vascular access that can assess hemodynamic alterations and early detect the access failure.

Conclusions

The present paper describes a new method suitable to on-line monitor the access flow in dialytic patients. An in-vivo validation test highlights a good correlation between the access flow estimated with our method and the one measured with the gold standard method [3]. The originality of our method consists in the use of pressure values usually available during the treatment without the necessity of supplementary device.

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