Time-dependent Pressure Distortion in a Catheter–Transducer System

Correction by Fast Flush

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Background: Distortion of the pressure wave by a liquid-filled catheter–transducer system leads most often to an overestimation in systolic arterial blood pressure in pulmonary and systemic circulations. The pressure distortion depends on the catheter–transducer frequency response. Many monitoring systems use either mechanical or electronic filters to reduce this distortion. Such filters assume, however, that the catheter–transducer frequency response does not change over time. The current study aimed to study the changes with time of the catheter–transducer frequency response and design a flush procedure to reverse these changes back to baseline.

Methods: An *in vitro* setup was devised to assess the catheter–transducer frequency response in conditions approximating some of those met in a clinical environment (slow flushing, 37°C, 48-h test). Several flush protocols were assessed.

Results: Within 48 h, catheter–transducer natural frequency decreased from 17.89 ± 0.36 (mean ± SD) to 7.35 ± 0.25 Hz, and the catheter–transducer damping coefficient increased from 0.234 ± 0.004 to 0.356 ± 0.010. Slow and rapid flushing by the flush device built into the pressure transducer did not correct these changes, which were reversed only by manual fast flush of the transducer and of the catheter. These changes and parallel changes in catheter–transducer compliance may be explained by bubbles inside the catheter–transducer.

Conclusions: Catheter–transducer-induced blood pressure distortion changes with time. This change may be reversed by a manual fast flush or "rocket flush" procedure, allowing a constant correction by a filter. (Key words: Blood pressure determination; equipment design; pressure transducers; signal processing; Swan-Ganz.)

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INVASIVE measurement of pulmonary arterial pressure is an important adjunct in the management of the critically ill patient. A liquid-filled catheter–transducer system to measure pulmonary arterial pressure is composed of a pressure transducer connected to a 110-cm-long flexible catheter. Liquid mass, liquid viscosity, and elasticity of the catheter wall have been shown to distort the blood pressure signal[1-4] from the pulmonary artery to the transducer output. From a practical point of view, numerous studies have shown that catheter–transducer systems most often lead to an overestimation of systolic blood pressure in the pulmonary circulation.[5-7] This overestimation increases with increasing heart rate and may reach 30% when heart rate is 180 beats/min.[5,6] This finding may complicate the accurate diagnosis of pulmonary hypertension.

This overestimation is explained because the pulsatile pressure signal becomes more amplified when it includes a growing proportion of frequency components approaching the catheter-transducer system resonant frequency. Such an error may be attenuated by in-line mechanical damping devices or electronic filters if the catheter-transducer system frequency response is known and constant. Moreover, some in-line mechanical damping devices may be adjusted according to a step test or "snap test" of the catheter-transducer system dynamic response.[5,8]

These correcting devices assume, however, that the catheter-transducer system frequency response does not vary over 2 days of use. To our knowledge, no study has addressed the changes over time of blood pressure

distortion. *In situ* testing of the dynamic response of catheter–transducer system by a snap test[5] is possible, but it is seldom performed in the clinical setting. Moreover, it has been found unreliable or difficult to interpret by some authors because the arterial pulsations frequently hide the dynamic response.[9]

Because the importance of blood pressure distortion depends on the characteristics of the input blood pressure signal and the behavior of the catheter–transducer system, the transfer function of the catheter–transducer system, which allows the calculation of the output pressure signal from any arbitrary pressure signal, has been a subject of intense interest for a long time.[1] The parameters of the transfer function of the catheter–transducer system are calculated using the frequency response of the catheter–transducer system. Therefore, the aims of this *in vitro* study were as follows: (1) to study the time dependence of the frequency response of the catheter–transducer system in conditions approximating some of those met in the clinical environment of a pulmonary artery catheter (temperature of 37°C, slow flushing of the catheter, 48 h of testing); (2) to identify the factors that induce this time dependence; and (3) to reverse the time-related change of the frequency response of the catheter–transducer system back to baseline rather than estimating it according to periodic snap tests of the catheter–transducer system dynamic response.

Materials and Methods

In Vitro *Test of a Liquid-filled Catheter–Transducer System*

We assembled three catheter–transducer systems using identical components for each: (1) a 7.5-French standard pulmonary artery catheter, 110 cm long (CAP 93A-834H-7.5F; Baxter Edwards Critical Care, Irvine, CA); and (2) a standard disposable pressure transducer with an associated flush device and three-way stopcock (33-260; Baxter Edwards Critical Care). An additional three-way stopcock was interposed between the flush inlet of the pressure transducer and the flush line of the pressurized saline bag. A 1-l saline bag was inserted in a cuff pressurized at 300 mmHg (Colson 331,001; Comeda, La Tronche, France), which was selected after checking that two other pressurizing cuffs (Baxter Travenol FRA 4,403; Ethox 4,010, Europe Medical, Le Faguet, France) created a similar pressure in the flush line.

Each catheter–transducer system was slowly primed with saline, and thereafter a slow continuous flush of the transducer and pulmonary artery catheter was maintained by the pressure transducer–associated flush device. The pulmonary artery catheter was maintained at a temperature of 37°C inside a pipe (100 cm long, 10 mm ID), with running water maintained at 37°C. Each test lasted 48 h.

In Vitro *Sine Pressure Wave Generation and Measurements*

The frequency response of each catheter–transducer system was tested using a sine wave generator (Hewlett-Packard 3,311A Function generator, Palo Alto, CA) from 1–40 Hz. The pressure waves were generated in the chamber of a hydraulic pressure generator (Biotek 601A; Biotek Instruments, Winooski, Vermont). This generator includes a saline-filled clear plastic dome closed by a sealed piston system. The piston volume displacements are small and allow the conversion of electrical signals into calibrated pressures. The plastic dome has two Luer lock ports. One port was connected to a hemostatic valve (Desilet-intro 7-8F valve 2,825.27; Plastimed, Le Plessis-Bouchard, France). The second port was connected to a three-way stopcock, which was in turn connected to the diaphragm valve of a pulmonary artery catheter introducer sheath. The latter valve allows a watertight introduction of catheters of various sizes into the dome. The intravascular tip of the 7.5-French pulmonary artery catheter, protruding from the thermostatized jacket, was introduced 10 mm into the plastic dome through the hemostatic valve. A high-frequency response catheter-tipped pressure transducer (Millar MPC-500; Millar Instruments, Houston, TX) was introduced 15 mm into the plastic dome through the other valve. The flush solution was allowed to leak from the chamber to the atmosphere through the three-way stopcock connecting the dome to the catheter-tipped pressure transducer, except during the generation of pressure waves inside the dome.

The disposable pressure transducer and the Millar catheter-tipped pressure transducer were calibrated simultaneously using the same water column. They were preamplified, respectively, by a Bridge amplifier (MacLab; AD Instruments, Castle Hill, Australia) and by a Millar TCB-500 Transducer Control Unit (Millar Instruments). Both signals were sampled in parallel at a frequency of 200 Hz by a multichannel analog-to-digital converter (MacLab/8; AD Instruments) and recorded on a Macintosh computer (Apple Computer, Cupertino, CA). The Millar catheter-tipped pressure transducer measured the reference pressure.
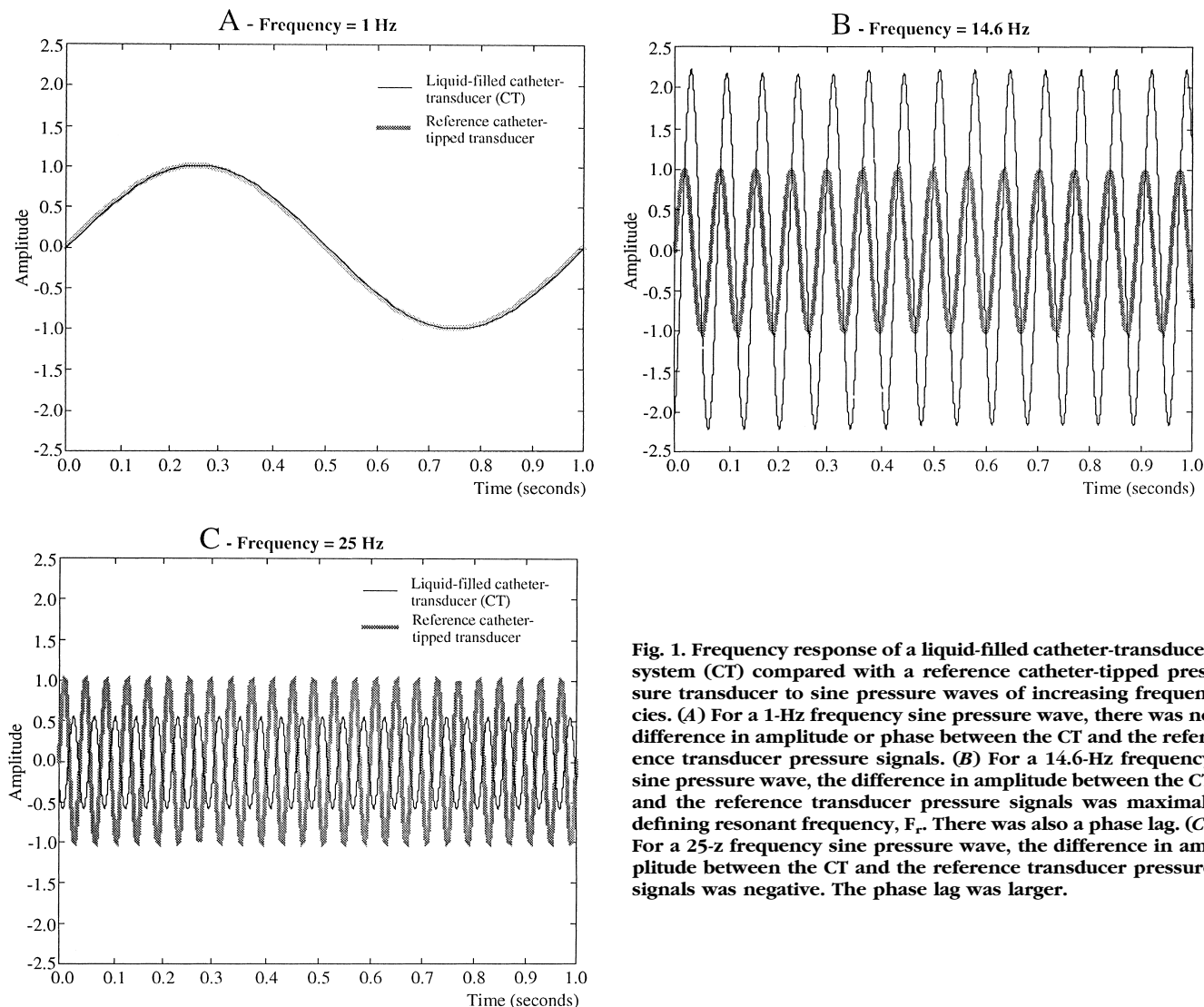
Fig. 1. Frequency response of a liquid-filled catheter-transducer system (CT) compared with a reference catheter-tipped pressure transducer to sine pressure waves of increasing frequencies. (*A*) For a 1-Hz frequency sine pressure wave, there was no difference in amplitude or phase between the CT and the reference transducer pressure signals. (*B*) For a 14.6-Hz frequency sine pressure wave, the difference in amplitude between the CT and the reference transducer pressure signals was maximal, defining resonant frequency, F_r. There was also a phase lag. (*C*) For a 25-z frequency sine pressure wave, the difference in amplitude between the CT and the reference transducer pressure signals was negative. The phase lag was larger.

Measurement of the Frequency Response of the Catheter-Transducer System

The pressure signal measured by the tested catheter-transducer system was compared with the reference pressure signal of the catheter-tipped pressure transducer for sine waves generated from 1–40 Hz by the hydraulic pressure generator (figs. 1A–C). The frequency response was measured in two steps. First, the response to a spectrum of frequencies from 1–40 Hz was scanned to detect the resonant frequency (F_r), *i.e.*, the frequency at which the amplitude of the pressure signal is maximal. Second, F_r was refined using 0.5-Hz increments in the 5-Hz range lower and higher than F_r. The whole procedure for measuring the frequency response lasted ≈ 2 min. The generation of pressure waves inside the dome of the hydraulic pressure generator during the measurement of the frequency response involved the interruption of the slow catheter-transducer system flushing and the closure of the chamber. The chamber was reopened to the atmosphere after the measurement of the pressure waves and the slow flushing resumed.

The harmonic analysis of the frequency response of the catheter-transducer system permitted the determination of the transfer function. The transfer function of the catheter-transducer system allows the calculation of the output pressure signal from any arbitrary pressure signal. The amplitude of the transfer function (fig. 2) was obtained from the amplitude ratio of the catheter-trans-
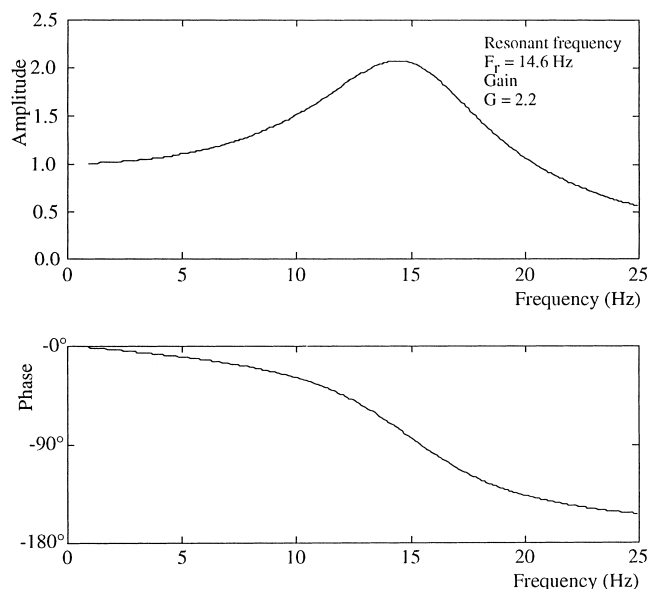
Fig. 2. The harmonic analysis of the frequency response of the liquid-filled catheter-transducer system (CT) allowed determination of the parameters of the transfer function. The maximal amplitude of the transfer function at resonant frequency (F_r), namely the gain (G), was obtained from the amplitude ratio of the CT signal to the reference signal of the catheter-tipped pressure transducer for F_r. The phase of the transfer function was obtained from the phase lag of the CT pressure signal *vs.* the reference pressure signal.

ducer system pressure signal to the reference pressure signal for all measured frequencies. The maximal amplitude of the transfer function at F_r is the gain, G. The phase of the transfer function (fig. 2) was obtained from the phase lag of the catheter-transducer system signal *versus* the reference signal of the catheter-tipped pressure transducer. We assumed that the frequency response of the catheter-transducer system was a second-order transfer function characterized by two parameters, the natural frequency (F_n) and the damping coefficient (ξ) (Appendix 1).

Dependence of the Transfer Function of the Catheter-Transducer System on Time and Fast Flush Protocol

The transfer function of the catheter-transducer system was measured 0, 1, 6, 24, and 48 h after the initial priming with saline. At each time, the measurement was repeated five times in series.

Because trapped air bubbles modify the frequency response of the catheter-transducer system,[10–12] a different catheter-transducer system fast flush protocol was performed initially in each of the three systems

being tested. The first protocol (P1 standard catheter-transducer system rapid flush) used the rapid flush device built into the pressure transducer. Pushing the button allowed a rapid flush by the pressurized saline bag. The P1 standard catheter-transducer system rapid flush was performed twice, for 5 s each. The second protocol (P2 whole catheter-transducer system rocket flush) involved a manual fast flush of the whole system by the fast injection of 5 ml saline using a syringe through the additional three-way stopcock interposed between the flush inlet of the pressure transducer and the flush line of the pressurized saline bag. To evaluate the necessity to flush the transducer separately from the catheter, the third protocol (P3 separate catheter-transducer system rocket flush) involved a manual fast flush of the catheter and of the transducer separately by the fast injection of 5 ml saline through the three-way stopcocks described previously.

After the last measurement at 48 h, two additional measurements after a fast flush were performed in all experiments. The first was aimed at observing the ability of the P1 standard catheter-transducer system rapid flush to reverse the time dependence of the frequency response of the system (test 1). The second was aimed at verifying that the three catheter-transducer systems retained similar behaviors at the end of all experiments after a P3 separate catheter-transducer system rocket flush (test 2).

Effect of Catheter Temperature on the Transfer Function of the Catheter-Transducer System

To extend the clinical pertinence of the study, we measured the transfer function of the catheter-transducer system after a P3 separate catheter-transducer system rocket flush not only at 37°C but also at ambient temperature.

Simulation of Catheter-Transducer System-induced Distortion of a Pulmonary Arterial Pressure Tracing

A pulmonary arterial occlusion pressure transient was measured during apnea in an anesthetized dog using a pressure microtransducer-tipped catheter (Millar SPC320) introduced in the lumen of the distal pressure channel of a 7.5-French pulmonary artery catheter (CAP 93A-631H-7.5F, Baxter Edwards Critical Care). The signal was sampled at a frequency of 100 Hz using the described apparatus. The data were stored in IBM PC format and reconverted into an analog electrical signal form by a PCL-812PG (Advantech, Taipei, Taiwan) using a PC-compatible AT 486DX com-

puter (ASC Inc., West Allis, WI). This analog electrical signal was then used to generate a pressure signal using the *in vitro* pressure generator.

The *in vitro*-generated pulmonary arterial occlusion pressure transient was measured in duplicate after the sine pressure waves in the three catheter-transducer systems at two temperatures (room temperature and 37°C) after our best version of the fast flush procedure, *i.e.*, a P3 separate rocket flush. The catheter-transducer system-induced distortion of the pulmonary arterial occlusion pressure tracing was illustrated by comparing the systolic, mean, diastolic, and wedge pressure values taken from the catheter-transducer system pressure with those taken from the reference catheter-tipped pressure transducer. A pulmonary capillary pressure value was obtained from the biexponential adjustment of the arterial occlusion pressure profile using a model of the pulmonary circulation including three compartments separated by two resistances.[13] As the early segment of the pulmonary arterial occlusion pressure profile decreases rapidly, it is sensitive to the catheter-transducer system-induced distortion. Therefore, the early exponential time constant value is also given.

Results

Dependence of the Transfer Function of the Catheter-Transducer System on Time and on the Initial Fast Flush Protocol

The parameters of the transfer function of the catheter-transducer system changed with time. Natural frequency decreased with a steeper slope during the first hours (fig. 3). In contrast, the damping coefficient increased with time. The relations of natural frequency and damping coefficient with time clearly differ depending on the initial catheter-transducer system fast flush protocol; the means and SDs of the five replicate measurements obtained at 0, 1, 6, 24, and 48 h do not overlap (Appendix 2).

Effect of the Final Catheter-Transducer System Fast Flush Protocol on the Time Dependence of the Transfer Function of the System

After the last measurement at 48 h, the efficacy of two catheter-transducer system fast flush protocols in restoring the transfer function of the catheter-transducer system back to baseline was tested in the three catheters (fig. 4 and Appendix 2). The final P1 standard catheter-transducer system rapid flush performed in test 1 had
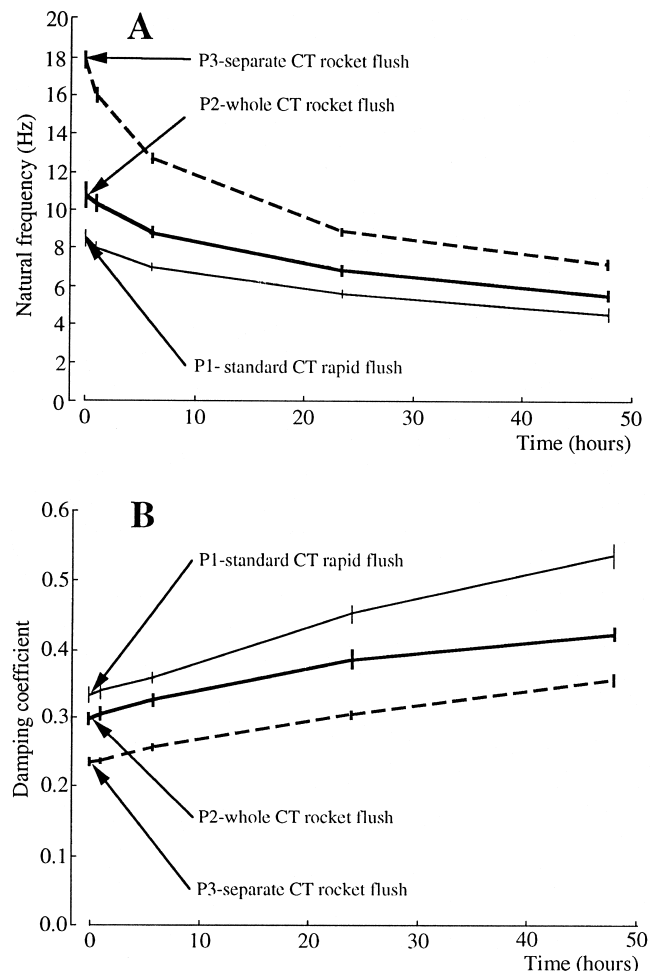

Fig. 3. Relations of (*A*) natural frequency and (*B*) damping coefficient of the transfer function of the liquid-filled catheter-transducer system (CT) to time. They differ depending on the initial CT fast flush protocol (see Materials and Methods). Each relation is drawn from the connection of means ± SD using five replicate measurements in a catheter at 0, 1, 6, 24, and 48 h.

essentially no effect. The final P3 separate catheter-transducer system rocket flush performed in test 2 enabled the natural frequency and the damping coefficient to reach a similar value for the three catheters regardless of their initial fast flush protocol, as observed from their means ± SDs and low coefficients of variation (17.07 ± 0.45, 0.6%; 0.234 ± 0.002, 0.9%, respectively). Two conclusions may be drawn from the high reproducibility of the transfer function parameter values of the three catheter-transducer systems. First, the final P3 separate catheter-transducer system rocket flush not only reversed the time-dependent changes of the transfer function of the catheter-transducer system but also the effects of the initial fast flush on the transfer function of
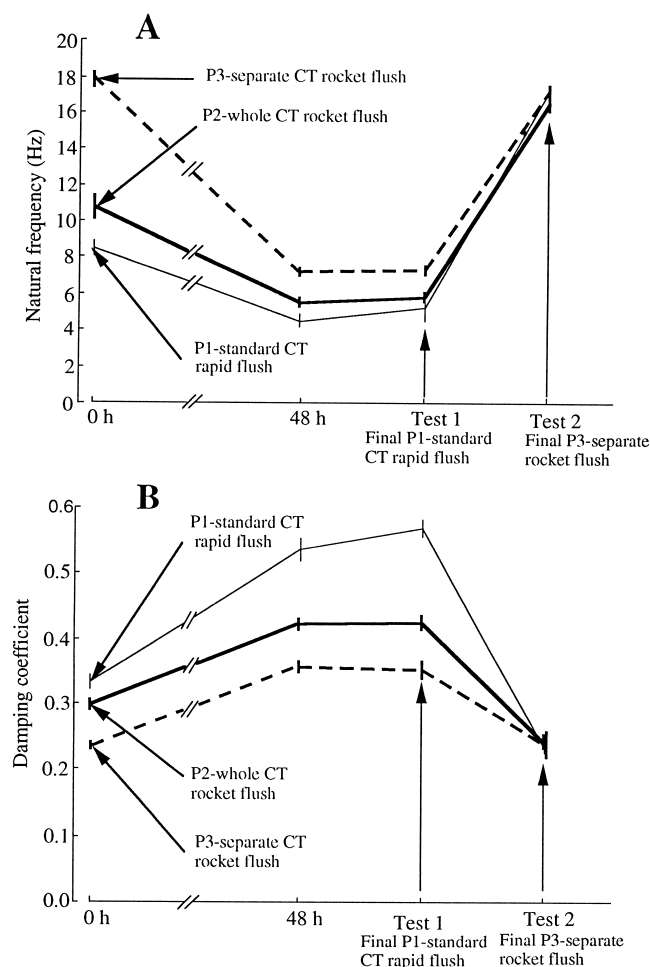
Fig. 4. Two fast flush protocols of a liquid-filled catheter-transducer system (CT) are tested to reverse the time-dependent changes at t = 48 h of (A) the CT natural frequency and (B) the damping coefficient. Final test 1 was performed using a protocol P1 standard CT rapid flush and final test 2 using a P3 separate CT rocket flush.

the system. Second, the measurements of the behavior of the catheter-transducer system in the current study are highly reproducible from one catheter-transducer system to the other.

Effect of Catheter Temperature on the Transfer Function of the Catheter-Transducer System

After a P3 catheter-transducer system separate rocket flush in the three catheters, natural frequency was 16.50 ± 0.33 Hz (n = 9) at ambient temperature *versus* 17.06 ± 0.47 Hz (n = 14) at 37°C, and the damping coefficient was 0.245 ± 0.015 (n = 9) at ambient temperature *versus* 0.234 ± 0.002 (n = 14) at 37°C. These

differences are small regarding transfer function of the catheter-transducer system.

Illustration of the Catheter-Transducer System-distorted Pulmonary Arterial Pressure Tracing

A pulmonary arterial occlusion pressure transient signal previously obtained in an anesthetized dog using a high-fidelity microtransducer-tipped pressure catheter was used to pilot the hydraulic pressure generator. To illustrate the effects of catheter-transducer system-induced distortion on the values taken from a pulmonary arterial occlusion pressure tracing, the generated pressure signal was measured (1) using the reference catheter-tipped pressure transducer; and (2) using the pulmonary artery catheter after a P3 separate catheter-transducer system rocket flush. The obtained values are displayed in table 1. Using the most efficient fast flush protocol, the estimate of pulmonary capillary pressure using the catheter-transducer system was not significantly modified compared with the estimate using the reference transducer. Overestimation of the pulmonary arterial systolic pressure by the catheter-transducer system, however, increased up to almost 5 mmHg.

Discussion

The current *in vitro* test of a pulmonary artery catheter in physical conditions approximating some of those met in a clinical environment (37°C, slow continuous flushing of the catheter, 48 h of monitoring) shows that the physical characteristics of a liquid-filled catheter-transducer system appear to change gradually in the hours after its assembly. The consequences of these changes are illustrated in an example in figures 5A and 5B, in which a baseline overestimation of the pulmonary arterial systolic pressure is amplified within 48 h. Another finding is the inability of the standard rapid flush device of the disposable transducer to prevent time-dependent changes of the transfer function of the catheter-transducer system. The most important finding of this study, however, is that a specific manual catheter-transducer system syringe fast flush, or "rocket flush," can prevent these time-dependent changes of the transfer function of the catheter-transducer system, enabling a correction based on constant catheter-transducer system transfer function parameters.

PROMONET *ET AL.*

Table 1. The Same Pulmonary Arterial Occlusion Pressure Transient was Measured Using Either a Liquid-filled Catheter–Transducer System or a Reference Pressure Transducer at t = 0 h

	Liquid-filled CT + P3-Separate CT Rocket Flush	Reference Catheter-tipped Pressure Transducer
Pulmonary arterial pressure (mmHg)		
Systolic	40.1 ± 0.6, 1.6%	35.2 ± 0.5, 1.4%
Mean	22.8 ± 0.3, 1.5%	22.8 ± 0.4, 1.8%
Diastolic	11.7 ± 0.2, 2.1%	12.2 ± 0.2, 1.4%
Pulmonary arterial wedge pressure (mmHg)	8.2 ± 0.1, 0.7%	8.2 ± 0.1, 1.2%
Postocclusion early rapid decrease time constant (sec^{-1})	12.2 ± 0.8, 6.8%	14.4 ± 0.6, 4.0%
Pulmonary capillary pressure (mmHg)	12.9 ± 0.4, 2.7%	13.4 ± 0.2, 1.2%

Data are mean ± SD. Variation coefficient = SD/m %. n = 12 measurements (3 CTs × 2 × 2; temperatures = ambient and at 37°C).

CT = Catheter-transducer system.

Catheter–Transducer System-induced Pressure Distortion

A catheter–transducer system induces a well-known distortion of the pressure signal.[1-7] It is most often an overestimation, which may reach 30% even after a careful initial standard rapid flush.[5,6] The current data confirm that the physical characteristics of a simple catheter-transducer system as described in the current study (one disposable pressure transducer, one pulmonary artery catheter) induce a distortion of the pressure signal. When the frequency components of the pressure signal are close to the resonant frequency, they become more and more amplified (figs. 1B and 2). When the frequency components of the pressure signal reach high frequencies, they become more and more attenuated (figs. 1C

and 2). The transfer function of the catheter-transducer system, therefore, is one source of distortion of the pressure signal. The distortion of the pressure signal, however, also depends on the frequency components of the pressure signal, which vary with the hemodynamic status (*e.g.,* tachycardia, increase in systolic volume).[4] The pressure distortion may be corrected by in-line mechanical damping devices[5,8,14] or by electronic and computerized filters.

Time-dependent Changes in the Transfer Function of the Catheter–Transducer System

The changes of the transfer function parameters of the catheter-transducer system within 48 h observed in the current study (fig. 3 and Appendix 2) modulate the
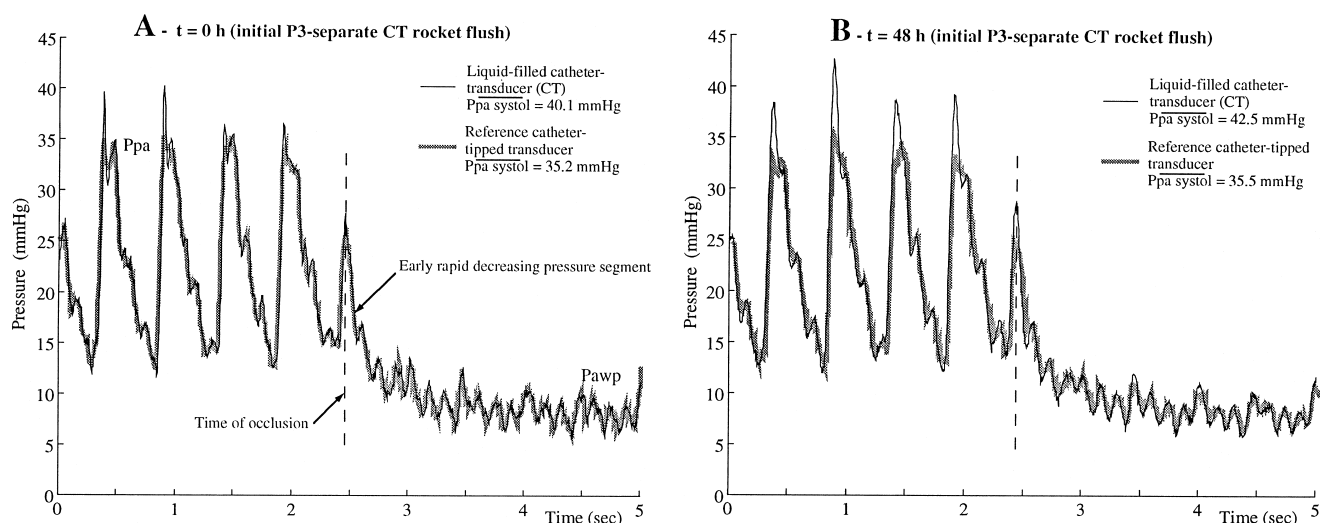

Fig. 5. (*A*) Baseline distortion of a pulmonary arterial occlusion pressure transient by a liquid-filled catheter-transducer system (CT; after an initial protocol [P]3 separate CT rocket flush) at t = 0 h. This distortion results here in a 5 mmHg overestimation of systolic pulmonary arterial pressure (table 1). (*B*) The pressure distortion is even more pronounced at t = 48 h, resulting in a 7 mmHg overestimation of systolic pulmonary arterial pressure. The pulmonary arterial occlusion pressure transient was generated using an *in vitro* pressure generator (see Materials and Methods).

importance of the pressure distortion (figs. 5A and 5B). The corrective mechanical or electronic filters assume that the transfer function of the catheter–transducer system remains constant. The current data question this assumption. If the time-dependent changes of the transfer function of the catheter–transducer system are not also reversed by the filters, unpredictable changes of a given pressure waveform may appear. Unless the changes of the transfer function of the catheter–transducer system with time are periodically accounted for or prevented, the pressure distortion is almost impossible to correct reliably.

Catheter Transducer Fast Flush Dependence of the Catheter–Transducer System Transfer Function

The transfer function of the catheter–transducer system differs depending on the initial catheter–transducer system fast flush protocol. This difference also changes with time, as evidenced by the differences in natural frequency and damping coefficient at 0, 1, 6, 24, and 48 h (fig. 3 and Appendix 2). Another finding is the inability of the standard rapid flush device built into the pressure transducer to prevent time-dependent changes of the transfer function of the system (fig. 4 and Appendix 2) and thus a change in the pressure distortion at 48 h. Three different cuffs around the saline bag pressurized at 300 mmHg could barely generate a pressure in the flush line > 150 mmHg. This may be a contributing factor in the inability of the standard rapid flush device built into the pressure transducer to prevent the time-dependent changes of the transfer function and pressure distortion.

The most important finding of this study, however, is that a separate manual fast flush by a syringe or rocket flush, not only of the catheter but also of the transducer itself (P3 separate catheter–transducer system rocket flush), can prevent the time-dependent changes in the transfer function of the catheter–transducer system. The final P3 separate catheter–transducer system rocket flush performed at 48 h allows the natural frequency and the damping coefficient of the three catheters to reach a similar value, regardless of the initial fast flush protocol (fig. 4). Not only did the final P3 separate catheter–transducer system rocket flush reestablish a transfer function of the catheter–transducer system at 48 h similar to that observed at time 0 but it also reversed the effects of the two other initial fast flush protocols on the transfer functions of the other catheter–transducer systems. This observation confirms the reproducibility of the transfer function of the catheter–transducer system
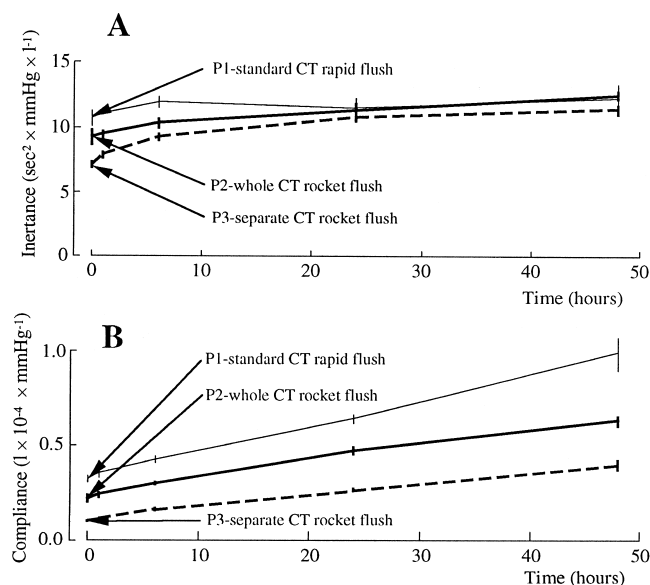

Fig. 6. Relation of liquid-filled catheter-transducer system (CT) (A) inertance and (B) compliance with time according to the initial CT fast flush protocol. Each relation is drawn from the connection of means ± SD of five replicate measurements in each catheter at each time period: 0, 1, 6, 24, and 48 h.

from one catheter to the other as long as a P3 separate catheter–transducer system rocket flush is performed periodically.

Relation between Catheter–Transducer System Time and Flush Dependence and Catheter–Transducer System Mechanical Characteristics

The catheter–transducer system mechanical parameters were obtained (Appendix 3[15–17]). The increases in inertance (see Appendix 3) within 48 h were low (15–60%) compared with increases in compliance (175–270%; fig. 6). All changes in inertance and compliance were reversed by the P3 separate catheter–transducer system rocket flush, demonstrating that the three catheter–transducer systems were manufactured with reproducible mechanical characteristics and that our experimental data were highly reproducible; further, the observations supported that the physical environment of the catheter did not notably alter the catheter compliance within 48 h. This study finds no direct evidence for the cause of the initial changes in inertance. We suggest, however, that the presence of microscopic air bubbles in the liquid-filled catheter–transducer system may explain three specific characteristics of the catheter–transducer system compliance behavior: (1) an initial level related to the initial catheter–transducer system fast flush protocol; (2) a

time-dependent increase; and (3) the reversal of this increase back to a common value for the three catheter-transducer systems by the P3 separate catheter-transducer system rocket flush. Previous studies have suggested that an increase in compliance may be related to the presence of bubbles in the catheter-transducer system liquid.[7,10-12] Moreover, Taylor *et al.*[11] demonstrated a linear relation between pulmonary artery catheter compliance and the volume of an air bubble introduced in the catheter. We made the hypothesis that the vaporization of air dissolved in saline inside the catheter-transducer system may generate bubbles. We suggest that the volume of these bubbles depends on the time-dependent growth of bubbles and on the efficacy of the flush.

Clinical Applicability

In clinical conditions, part of the catheter is in the air at ambient temperature while the remaining part is intravascular at body temperature. The current data show, confirming previous data,[6] that the temperature of the catheter environment (37°C *vs.* ambient) does not have a critical effect on the transfer function of the catheter-transducer system. From a practical point of view, the current data also emphasize the need for manufacturers to improve the efficacy of the rapid flush devices built into the disposable pressure transducers. A specific manual catheter-transducer system syringe fast flush or rocket flush can prevent time-dependent changes of the transfer function of the catheter-transducer system, enabling a correction by a filter with a fixed set of parameters. No interpretation of repeated snap tests is needed, only a rocket flush at regular time intervals. To avoid any damage in the pulmonary circulation, however, the rocket flush should not be applied on a routine basis without checking that the pulmonary artery catheter is not in a wedge position. Finally, the conclusions of this study are not limited to the clinical measurement of pulmonary arterial pressure. They also apply to the invasive measurement of systolic arterial blood pressure in the systemic circulation, in which the possibility of catheter-transducer system-induced distortions have been demonstrated repeatedly.[7,8,10] Some attention should be given to these distortions, especially when variations in systolic arterial blood pressure are analyzed to assess preload during mechanical ventilation.[18,19]

Appendix 1: Parameters of the Catheter–Transducer System Transfer Function

We assumed that the frequency response of the catheter-transducer system was a second-order transfer function characterized by two parameters, the natural frequency (F_n), which is the oscillation frequency resulting from a step pressure change, and the damping coefficient (ξ). Using this model, the ratio $P_2(f)/P_1(f)$ reads:

$$\frac{P_2(f)}{P_1(f)} = \frac{1}{-\frac{f^2}{F_n^2} + 2j\xi\frac{f}{F_n} + 1} \tag{1}$$

where j is the imaginary unit, P_1 is the pressure signal output of the transducer, P_2 is the driving pressure at the intravascular tip of the catheter, and f is the frequency.

The damping coefficient ξ is calculated from[5,9]:

$$\xi = \sqrt{\frac{1 - \sqrt{1 - \frac{1}{G^2}}}{2}} \tag{2}$$

where

$$G = \frac{\|P_1(F_r)\|}{\|P_1(0)\|} \tag{3}$$

where F_r is resonant frequency (see Materials and Methods). The natural frequency F_n is calculated from[9]:

$$F_n = \frac{F_r}{\sqrt{1 - 2\xi^2}} \tag{4}$$

The transfer function of the catheter-transducer system also may be related to the mechanical parameters of the catheter-transducer system (resistance, inertance, and compliance; Appendix 3).

Appendix 2: Dependence of the Transfer Function Parameters of the Catheter–Transducer System on Time and on Initial Fast Flush Protocol

The changes of natural frequency and damping coefficient at 0, 1, 6, 24, and 48 h are given in detail in table 2. These changes clearly differ depending on the initial CT fast flush protocol. The results of two CT fast flush protocols in restoring the CT transfer function back to baseline at 48 h are also given in detail (final test 1 and final test 2) in table 2.

Appendix 3: Mechanical Parameters of the Catheter–Transducer System

Methods

To relate the frequency response of the catheter-transducer system to the mechanical parameters of the catheter-transducer system (resistance [R], inertance [I], and compliance [C]), the frequency re-

Table 2. Dependence of CT Transfer Function Parameters on Time and on Initial Fast Flush Protocol

Time (h)	P1-standard CT Rapid Flush		P2-whole CT Rocket Flush		P3-separate CT Rocket Flush	
	Natural Frequency	Damping Coefficient	Natural Frequency	Damping Coefficient	Natural Frequency	Damping Coefficient
0	8.45 ± 0.41	0.332 ± 0.008	10.83 ± 0.52	0.297 ± 0.006	17.89 ± 0.36	0.234 ± 0.004
1	7.98 ± 0.27	0.338 ± 0.011	10.31 ± 0.25	0.305 ± 0.008	15.96 ± 0.32	0.237 ± 0.003
6	6.98 ± 0.19	0.360 ± 0.008	8.85 ± 0.16	0.326 ± 0.007	12.49 ± 0.22	0.257 ± 0.003
24	5.80 ± 0.26	0.447 ± 0.012	6.81 ± 0.16	0.387 ± 0.012	9.21 ± 0.09	0.302 ± 0.008
48	4.59 ± 0.35	0.532 ± 0.016	5.63 ± 0.16	0.424 ± 0.008	7.35 ± 0.25	0.356 ± 0.010
Test 1 P1-standard flush	5.32 ± 0.78	0.570 ± 0.013	5.85 ± 0.21	0.421 ± 0.010	7.37 ± 0.14	0.351 ± 0.013
Test 2 P3-separate flush	17.30 ± 0.03	0.232 ± 0.001	16.56 ± 0.29	0.237 ± 0.001	17.36 ± 0.39	0.234 ± 0.005

Data are mean ± SD (5 replicates). Three catheters are tested, each after a different initial fast flush protocol. At 48 h, two additional tests are performed on the three catheters. In final test 1, a P1-standard CT rapid flush is performed. In final test 2, a P3-separate CT rocket flush is performed.

CT = catheter-transducer system.

sponse of the catheter-transducer system is generally described by a second-order differential equation equivalent to the transfer function in equation 1[15,16]:

$$IC\frac{d^2P_2}{d^2t} + RC\frac{dP_2}{dt} + P_2 = P_1 \quad (5)$$

where I is the liquid inertance of the catheter, *i.e.*, the coefficient relating the pressure increment to the flow acceleration. Inertance is proportional to the volumetric mass of the liquid inside the catheter and to the catheter length. It is inversely proportional to the cross-sectional area. C is the compliance of the catheter-transducer system, R is the liquid resistance of the catheter, P_1 is the pressure signal output of the transducer, P_2 is the driving pressure at the intravascular tip of the catheter, and t is time.

This transfer function is characterized by a natural frequency (F_n) and by a damping coefficient (ξ). These two parameters are obtained by identification from equations 1 and 5[9]:

$$F_n = \frac{1}{2\pi\sqrt{IC}} \quad (6)$$

$$\xi = \frac{R}{2}\sqrt{\frac{C}{I}} \quad (7)$$

The parameters F_n and ξ of the transfer function of the catheter-transducer system allow the calculation of I and C if R is measured independently. The measurement of the pressure difference δP and of the saline flow (Q) through the catheter allowed the calculation of the resistance of the catheter,[17] which is the major component of the catheter-transducer system resistance.[11] The external port of the pulmonary artery catheter was connected through a three-way stopcock to the infusion line of the saline bag and to the disposable pressure transducer while the intravascular extremity of the catheter was open to the atmospheric pressure into a glass reservoir. The filling time of the reservoir allowed measurement of the constant flow through the catheter.

Results

Resistance is 373 ± 12 mmHg · s · l⁻¹ (mean ± SD, n = 3). Catheter-transducer system inertance increases from 0 to 48 h, ranging from 15–60% with time with a marked initial increment (fig. 6).

Catheter-transducer system compliance presents a linear increase with time, with an increase ranging from 175–270%. The relations between catheter-transducer system compliance and time clearly differ according to the protocol of initial catheter-transducer system fast flush (fig. 6). Compliance during test 2 (P3 separate catheter-transducer system rocket flush) reached similar values of 0.115, 0.122, and 0.115 10⁻⁴ l/mmHg for initial P1 standard catheter-transducer system rapid flush and P2 whole and P3 separate catheter-transducer system rocket flushes, respectively. The inertance and compliance of the three catheter-transducer systems in test 2 reflect the high reproducibility of the catheter-transducer system mechanical characteristics from one system to the other, as observed from their means ± SDs and low coefficients of variation (7.45 ± 0.15 s² · mmHg · l⁻¹, 1.99%; 0.118 ± 0.004 10⁻⁴ l/mmHg, 3.52%).

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