Feasibility of In Vivo Pressure Measurement Using a Pressure-Tip Catheter via Transventricular Puncture

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Pressure-tip catheters (PTCs) are used to evaluate ventricular mechanics during surgical repair of congenital heart disease in children. Studies in infants require miniaturized sensors. We compared the safety and accuracy of a 2-Fr ultraminiature PTC with a 5-Fr PTC. In 10 piglets (weight 19–22 kg), a 5-Fr PTC was inserted through a 3-mm apical puncture with a #11 blade. A 20-gauge angiogater was inserted using a separate site. A 2-Fr PTC was threaded through the angiocatheter lumen. The angiocatheter was withdrawn, leaving the 2-Fr PTC within the left ventricle (LV). Left ventricular pressure (LVP) changes were measured during three inferior vena cava occlusions. Reliability coefficients demonstrated correlation between the 2-Fr PTC and 5-Fr PTC for LV end-diastolic pressure (0.90–0.95), peak LVP (0.92–0.99), and the maximal (0.87–0.93) and minimal (0.89–0.94) first derivatives of LVP. Bland-Altman analysis demonstrated agreement for all variables. Blood loss was trivial with pressure manipulation and catheter placement and removal. Pressure measurements using the 2-Fr PTC were accurate and comparable with those from the 5-Fr PTC. Transventricular placement of a 2-Fr PTC is feasible and should allow evaluation of ventricular mechanics during surgical repair of congenital heart disease. ASAIO Journal 2010; 56:194–199.

Accurate intracardiac pressure measurement is fundamental to assess ventricular mechanics intraoperatively. Fluid-filled catheter systems are relatively inexpensive and durable; however, because these pressure signals are transmitted through an interfused fluid column to an external transducer, they may be distorted with respect to time and amplitude. These transducer systems are limited by a 0–30 Hz frequency response,1–3 a resonant frequency of 5–75 Hz, and damping (damping coefficient systems are limited by a 0–30 Hz frequency response,1–3 a res-
1985). The Columbia University Institutional Animal Care and Use Committee approved the experimental protocol.

**Animal Preparation**

Data was collected in 10 Yorkshire piglets (weight 19–22 kg). These pigs were part of a broader study requiring serial pressure measurement recordings, during an evaluation of the benefits of biventricular pacing optimization. They were chosen because their LV volume and pressure are similar to those of a neonate with single ventricle physiology. Pigs were anesthetized intramuscularly with atropine sulfate (0.02 mg/kg), ketamine hydrochloride (20 mg/kg), and xylazine (0.5 mg/kg), followed by oral endotracheal intubation. They were mechanically ventilated using 100% oxygen and titrated isoflurane (1.75%–2.5%). Normal saline was administered intravenously at 10 ml/kg/h for the first hour and 5 ml/kg/h thereafter. Heart rate and body temperature were monitored.

**Instrumentation**

A median sternotomy was performed, the pericardium was opened longitudinally, and the inferior vena cava (IVC) was snared. Heparin was administered intravenously (100 U/kg). The first pressure catheter, a 5-Fr PTC (Millar Instruments, Houston, TX), was placed through a 3-mm apical puncture with a #11 blade within a 4-0 prolene purse-string suture at the apex. Without using a purse-string suture, the second PTC was placed at a separate LV site. A 20-gauge angiocatheter with an introducer was inserted through the LV wall near the apex. The introducer was withdrawn, and a 2-Fr PTC (Millar Instruments, Houston, TX) was threaded through the lumen. The angiocatheter was then withdrawn, leaving the 2-Fr PTC within the LV cavity.

The LV apex in piglets is very thin and was chosen as the catheter placement site to approximate the size of an infant’s LV anterior wall. Throughout the experiment, the myocardium was inspected for bleeding from catheter insertion sites. Both catheters were calibrated at 0 and 20 mm Hg, using room temperature normal saline in a graduated cylinder, immediately before insertion and after each experiment.

**Pressure Measurements**

Left ventricular pressure was acutely reduced by transient IVC occlusion. During the dynamic pressure manipulation period, beat-to-beat pressure changes were simultaneously recorded by both catheters. These pressure changes were analogous to those seen intraoperatively upon initiation of cardiopulmonary bypass (CPB). Three consecutive IVC occlusions, each lasting 10–15 seconds, were performed per experiment. The lungs were held at end-expiration during the entire IVC occlusion. Pressure and electrocardiographic data were digitized at 200 Hz, using a 16-channel analog-to-digital converter (AD Instruments, Milford, CA), and recorded on a portable computer (Apple Computer, Cupertino, CA).

**Pressure Sensor**

The 2-Fr PTC (SPC-320; Millar Instruments, Inc., Houston, TX) consists of an electronic interface and a polyurethane catheter without a lumen. The catheter contains a piezoelectric strain gauge (full Wheatstone bridge), side mounted at the tip. The pressure sensitivity is 5 mV/V/mm Hg, with a range of −50 to 300 mm Hg and a temperature band of ±3 mm Hg, from −20°C to 38°C, with <6 mm Hg drift over a 12-hour span. The 5 Fr-PTC (MPC-500; Millar Instruments, Inc., Houston, TX) is also a nonlumen polyurethane catheter, with an electronic interface and pressure sensor side mounted at its tip. It also has a pressure sensitivity of 5 mV/V/mm Hg, with a range of −50 to 300 mm Hg and a temperature band of ±1 mm Hg, from −20°C to 38°C, with <6 mm Hg drift over a 12-hour span.

**Data Analysis**

Pressure analysis was performed offline using custom routines implemented in MATLAB (The MathWorks, Inc., Natick, MA). Thirty episodes of dynamic LVP change were recorded. Left ventricular pressure was digitally differentiated. Left ventricular end-diastolic pressure (LVEDP) was identified as the point before the LVP rapid upstroke, before dP/dt exceeded 10% of its maximal value (dP/dt_max). For each serial beat acquired during IVC occlusion, LVEDP, peak systolic pressure (peak LVP), and the dP/dt_max and minimal (dP/dt_min) first derivative were analyzed for each PTC. The beat preceding the first LVEDP decrease defined the first beat, and the lowest LVEDP defined the last beat analyzed during IVC occlusion.

**Statistical Analysis**

Reliability coefficients (intraclass correlations) were generated for each LVP variable (LVEDP, peak LVP, dP/dt_max, and dP/dt_min), for all 30 IVC occlusions, using mixed model technology (SAS, PROC MIXED, SAS Institute, Inc., Cary, NC). A random intercept model was fit, which generated the intraclass correlation: $d/(d + s^2)$, where $d$ = intersubject variability and $s^2$ = intrasubject variability.

Bland-Altman analysis was also performed for each pressure variable (LVEDP, peak LVP, dP/dt_max, and dP/dt_min), for all 30 IVC occlusions. Bias and 95% confidence intervals were calculated using the following formulas: Bias = $d$ (where $d =$ the mean difference between the two measurements), and 95% confidence intervals = $d$ ± 2$s$ (where $s =$ the SD of the differences). The multiple measurements taken for each IVC occlusion were summarized as means and the difference in means. Bland-Altman analysis was then performed for each pressure variable.

**Results**

Recorded pressure data, obtained during dynamic preload reduction, allowed for simultaneous comparison of the two catheters.

**Pressures**

During each transient IVC occlusion, beat-to-beat pressure variations were elicited and simultaneously recorded. This procedure was repeated three times per experiment, with peak LVP and LVEDP measured and compared for each heartbeat during dynamic pressure reduction. **Figure 1** shows represen-
tative pressure data obtained by IVC occlusion. Peak LVP ranged from 111.6 to 34.0 mm Hg for the 2-Fr PTC and 108.2 to 34.0 mm Hg for the 5-Fr PTC. LVEDP ranged from 20.5 to 1.1 mm Hg for the 2-Fr PTC and 19.5 to 1.1 mm Hg for the 5-Fr PTC.

The results from reliability coefficients generated during the 10 experiments are shown in Table 1 and demonstrate correlation between the catheters for peak LVP and LVEDP, with reliability coefficients of \( \geq 0.92 \) and \( \geq 0.90 \), respectively. Figure 2 is a Bland-Altman plot of peak LVP, comparing measurements obtained by the 2-Fr PTC and 5-Fr PTC. Over 30 episodes of pressure manipulation, peak LVP had a 0.6 mm Hg bias, with a 95% confidence interval of \(-3.4 \) to \(4.5 \) mm Hg. Figure 3 is a Bland-Altman plot comparing LVEDP measurements. Analysis demonstrated a 0.4 mm Hg bias, with a 95% confidence interval of \(-1.9 \) to \(2.6 \) mm Hg.

**Derivatives**

The \( dP/dt \) measurements, obtained during each of the 30 episodes, were digitally calculated. \( dP/dt_{\text{max}} \) ranged from 4668 to 280 mm Hg/s for the 2-Fr PTC and 5120 to 288 mm Hg/s for the 5-Fr PTC. \( dP/dt_{\text{min}} \) ranged from \(-211 \) to \(-1964 \) mm Hg/s for the 2-Fr PTC and \(-210 \) to \(-1948 \) mm Hg/s for the 5-Fr PTC.

Reliability coefficients generated to compare \( dP/dt \) measurements from the two PTCs are shown in Table 1. Correlation between the catheters, with respect to \( dP/dt_{\text{max}} \) and \( dP/dt_{\text{min}} \), is demonstrated with reliability coefficients of \( \geq 0.87 \) and \( \geq 0.89 \), respectively.

Figure 4 is a Bland-Altman plot of \( dP/dt_{\text{max}} \), performed to compare pressure measurements from the 2-Fr PTC and 5-Fr PTC. Bland-Altman analysis demonstrated a \(-24 \) mm Hg bias, with a 95% confidence interval of \(-176 \) to \(128 \) mm Hg/s. Figure 5 is a Bland-Altman plot of \( dP/dt_{\text{min}} \). Analysis demon-

### Table 1. Reliability Coefficients

<table>
<thead>
<tr>
<th>Variable</th>
<th>IVC 1</th>
<th>IVC 2</th>
<th>IVC 3</th>
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</thead>
<tbody>
<tr>
<td>Peak LVP</td>
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<td>0.96</td>
<td>0.99</td>
</tr>
<tr>
<td>LVEDP</td>
<td>0.91</td>
<td>0.90</td>
<td>0.95</td>
</tr>
<tr>
<td>( dP/dt_{\text{max}} )</td>
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</tr>
<tr>
<td>( dP/dt_{\text{min}} )</td>
<td>0.89</td>
<td>0.92</td>
<td>0.94</td>
</tr>
</tbody>
</table>

IVC, inferior vena caval occlusion; Peak LVP, peak left ventricular pressure; LVEDP, left ventricular end-diastolic pressure; \( dP/dt_{\text{max}} \), maximum rate of increase of ventricular pressure; \( dP/dt_{\text{min}} \), maximum rate of decrease of ventricular pressure.
strated a 22.9 mm Hg/s bias, with a 95% confidence interval of −65 to 111 mm Hg/s.

**Insertion Technique**

The transventricular insertion technique, which did not require a purse-string suture, was successfully employed using the 2-Fr PTC in all 10 experiments. Only trivial blood loss occurred during pressure manipulation and catheter placement and removal, and any bleeding resulting from catheter withdrawal was limited and resolved spontaneously. The catheter position was stable during IVC occlusion, and it was not displaced during any of the experiments.

**Discussion**

Ventricular function and cardiac work are crucial determinants of outcomes for patients with palliated single ventricle anatomy. These patients often require multiple reoperations utilizing CPB, with the long-term effects of such repeated insults on myocardial function largely unknown. The intraoperative assessment of ventricular mechanics during these palliative surgeries could lead to insight and innovation, with respect to surgical technique, myocardial preservation, or immediate pre- and postoperative management.

Our group has previously studied patients undergoing Fontan completion, linking increased preoperative ventricular stiffness to increased postoperative morbidity. Tanoue et al. investigated older patients with single ventricle physiology before and after BDG and Fontan procedures. They found that end-diastolic ventricular volume decreased step wise after both surgeries, allowing for increased ventricular efficiency, and concluded that the interposed BDG procedure is an important consideration factor in treating high-risk Fontan candidates.

Currently, there is controversy concerning the type of initial palliation for single ventricle patients, with respect to the pulmonary blood flow supply method, and it is the subject of an ongoing randomized controlled trial. Two options are available and differ from sites of anastomosis: the systemic artery to pulmonary artery conduit and right ventricle to pulmonary artery conduit. Bove and coworkers have developed multiscale computer models to predict postoperative hemodynamic changes based on initial surgical palliation. The use of miniaturized catheters should allow our methods to be applied to directly evaluate ventricular mechanics in these vulnerable patients undergoing initial surgical palliation.

This work requires high-fidelity ventricular pressure measurements. Fluid-filled catheters with externally placed transducers have insufficient temporal resolution to accurately assess the ventricular pressure changes necessary for studying ventricular mechanics. Therefore, only PTCs should be used for high-fidelity measurements. We compared a smaller 2-Fr PTC with a catheter currently used at Columbia University Medical Center. The 5-Fr PTC has been utilized intraoperatively in older children undergoing Fontan completion and Tetralogy of Fallot repair, and more than 175 such studies using this catheter have been performed since 1997 at our medical center.

Before CPB, the catheter was inserted via a 3-mm apical puncture with a #11 blade within a purse-string suture; the 2-Fr PTC was inserted using the transventricular needle insertion technique described above. Pressure changes induced by transient IVC occlusion were then recorded simultaneously.

**Pressures**

The 2-Fr PTC satisfies all requirements for a high-fidelity manometer, with pressure sensitivities comparable with the...
5-Fr PTC currently used. Reliability coefficient analysis of peak LVP and LVEDP recordings showed that the two catheters compared very well, with coefficients of ≥0.90.

Bland-Altman analyses were also performed to assess agreement between the two clinical measurement methods.14 Bland-Altman analysis of peak LVP demonstrated agreement between the two catheters with a <1 mm Hg bias, with a 95% confidence interval of −3.4 to 4.5 mm Hg, given that the peak LVP ranged from 112 to 34 mm Hg. In fact, Figure 3 demonstrates that the majority of data points clustered within ±2 mm Hg, with relatively few outliers, suggesting that the LVEDP demonstrated somewhat less agreement. The 0.4 mm Hg bias was lower, with a 95% confidence interval range of −1.9 to 2.6 mm Hg; however, the overall LVEDP pressure range was 20.5–1.1 mm Hg, much lower than peak LVPs encountered.

Overall, the pressures encountered were within normal limits. The LVEDP range found in Fontan patients is 2–13 mm Hg, with the mean LVEDP of 7.7 ± 2.6 in right dominant ventricles and 11.2 ± 1.9 in left dominant ventricles.9 When reviewing Figure 2, it appears that most LVEDP measurements clustered near the bias line at pressures of <7 mm Hg, with more variation noted at pressures >7 mm Hg. This could be secondary to catheter tip entrapment within a ventricular trabeculation during pressure manipulation or thrombus formation at the catheter tip. Alternatively, if the micromanometers were positioned at different levels within the dP/dt max ventricular cavity, physical pressure gradients arising during diastole could account for the variations encountered.21,22

Derivatives

Reliability coefficient analysis demonstrated very comparable pressure recordings for dP/dt max and dP/dt min, with coefficients of ≥0.87. Bland-Altman analysis also demonstrated an agreement between measurements from the two catheters. A −24 mm Hg/s dP/dt max bias, with a 95% confidence interval of ±152 mm Hg/s, is acceptable, given the dP/dt max range 5120–280 mm Hg/s. Similarly, a 23 mm Hg/s dP/dt min bias, with a 95% confidence interval of ±88 mm Hg/s, is also acceptable,22 given the dP/dt min range −210 to −1948 mm Hg/s.

Insertion Technique

The transventricular insertion technique rationale was based on the routine use, at our institution, of 18- to 20-gauge needles to de-air the heart (ventricles) during withdrawal from CPB. This insertion technique was easily performed and provided stable catheter position, without excessive bleeding or ectopy. In addition, all bleeding stopped spontaneously immediately after catheter removal. This technique avoided excessive catheter manipulation retrograde across the aortic valve during placement, thereby minimizing the risks of aortic valve or coronary artery injury, while allowing the high-fidelity ventricular pressure measurements necessary for studying ventricular mechanics.

Limitations

An important limitation was the inability to verify baseline calibrations after insertion, an advantage that fluid-filled pressure systems have over PTCs. A PTC with a lumen capable of pressure passage to an external port has been reported to address this issue.23 Standardization of insertion depth or visualization of exact catheter tip position within the ventricle during catheter insertion may allow for tighter agreement in future experiments, especially regarding LVEDP measurements. Furthermore, although it was unlikely that the catheters were in mechanical contact, electrical field interference induced by currents in the sensors was possible. In the future, one ventricular catheter will be used at a time to overcome this possible limitation. Recent advancements in the development of ultraminiature PTCs have allowed for further downsizing of the catheters to 1.0 Fr. These catheters are currently widely used in studies of ventricular mechanics in mice24 and will ultimately be refined for clinical application.

Conclusion

In infants and young children undergoing congenital heart defect repair, thorough evaluation of intraoperative ventricular function has been limited by available technology. This study has shown that, in piglet hearts, pressure recordings obtained from the ultraminiature 2-Fr PTC are comparable with those from the larger 5-Fr PTC currently used. In addition, our novel transventricular insertion technique remained stable throughout our experiments and was easily performed and well tolerated. We hope to eventually use these methods and technologies to study intraoperative ventricular mechanics in infants and small children undergoing open-heart surgical procedures.

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