Case Presentation

A 72 year-old woman underwent aortic valve replacement (AVR) for severe aortic stenosis. At 5 feet tall and 50 kg, she had a small aortic valve annulus and a #19 bioprosthetic valve was inserted uneventfully. Following separation from cardiopulmonary bypass (CPB) on milrinone and norepinephrine, the valve was interrogated with TEE. All leaflets were visualized as having good mobility and the annulus appeared to be stable without any abnormal paravalvular leak. Upon spectral Doppler examination, however, the peak gradient measured almost 40 mmHg.

What is the appropriate management?

Usefulness of Gradients

Obtaining a post-procedural transvalvular gradient is part of a comprehensive interrogation following any cardiac valve replacement. It can serve as a rough screening tool to rule out significant valvular obstruction that might be caused by a dysfunctional leaflet or retained native tissue. Gradients are particularly useful when 2D imaging of the leaflets is difficult due to shadowing and reverberation artifacts.

Caution needs to be used in interpretation of these gradients, however. The intraoperative echocardiographer needs to be aware of exactly what is being measured, as well as the limitations of Doppler assessment in the immediate post-CPB period. This will help to avoid erroneously diagnosing prosthetic valve dysfunction, or raising concerns about patient-prosthetic mismatch, a situation with potentially detrimental consequences to the patient.

Types of Gradients
There are several types of gradients that can be reported with prosthetic valves (Figure 1). It is important to note the difference between "peak instantaneous" gradient, which is calculated using Doppler ultrasound, and "peak-to-peak" gradient, which is measured during cardiac catheterization. Although the difference between the two tends to be small, they are not interchangeable. Because of this, the "mean" gradient tends to be reported when dealing with prosthetic valves.

**Figure 1**
Because the peak left ventricular (LV) and aortic (Ao) pressures do not occur simultaneously, there is a small difference between the "peak" and "peak-to-peak" gradients. The mean gradient is indicated by the shaded area between the two curves.

### The (over-) Simplified Bernoulli Equation

The Bernoulli equation is a derivation of Conservation of Momentum principles and used in fluid mechanics. The full expression (Figure 2) assumes steady flow and states that, in the absence of frictional (thermal) losses, the total mechanical energy at any point along a streamline remains constant. This total mechanical energy is the sum of the pressure energy (static pressure), kinetic energy (motion), and potential energy (height).

\[ p + \rho \left( \frac{V^2}{2} \right) + \rho gz = H \]

**Figure 2**
The steady flow Bernoulli equation describes the total energy (H) at any point along a streamline.

- \( p \) = pressure
- \( \rho \) = density
- \( V \) = velocity
- \( g \) = gravity
- \( z \) = height

When trying to find the pressure drop (i.e. gradient) between 2 points located on streamlines of similar heights, the term \( \rho gz \) can be ignored. The density of blood is assumed to be 1.06 g/cm\(^3\), so the Bernoulli equation can be rewritten to:

\[ p_1 - p_2 = 4(V_2^2 - V_1^2) \]

For convenience sake, the proximal velocity is often assumed to be much smaller than the distal velocity and is neglected. Ignoring \( V_1 \) yields the familiar simplified Bernoulli equation, which allows the echocardiographer to quickly estimate the peak gradient:

\[ \Delta p = 4V^2 \]
While the simplified Bernoulli equation is convenient to use, some of the assumptions made are not necessarily valid following implantation of prosthetic valves. In particular, ignoring the proximal velocity can lead to an overestimation of the peak gradient by 28% or more.\textsuperscript{1} For this reason, the more complete Bernoulli equation should be used to calculate peak gradients following valve replacements. It should also be recognized that gradients are flow-dependent and that flows (i.e. cardiac output) are usually higher following separation from CPB than the patient will have after being discharged home. This is particularly significant for bioprosthetic and small (≤23mm) mechanical valves in the aortic position, which show a 5-10% decrease in gradients on 3-5 month follow-up.\textsuperscript{2}

**Pressure Recovery**

As fluid moves through an orifice, its total energy equals the sum of its kinetic and pressure energy minus any thermal loss, and will remain constant on each side of the orifice (Conservation principle). Similarly, as blood moves through a prosthetic valve opening, the product of its pressure and velocity must remain the same except for energy lost as heat (i.e. energy loss due to turbulent flow). When continuous wave Doppler (CWD) is placed through the opening of a prosthetic valve, it measures the velocity at the vena contracta, where velocity is highest and pressure is lowest. As blood moves downstream from the valve, however, velocity slows and some of the kinetic energy is converted back to pressure (see Figure 3). The majority of pressure recovery occurs 2 - 5 cm downstream from the vena contracta. By not taking this pressure recovery into account, Doppler derived gradients overestimate those obtained from catheterization by 5 to 15 mmHg or more depending upon valve type and size.\textsuperscript{3}

![Figure 3](https://via.placeholder.com/150)

As a catheter is pulled back from the aortic valve, the pressure increases due to pressure recovery. Because of energy loss due to turbulent flow (i.e. heat), not all energy is available to be “recovered.”

(Adapted from Chambers, Heart 1996)\textsuperscript{4}

**Patient Prosthesis Mismatch**

An ideal prosthetic valve would have the same orifice area as the patient’s non-diseased native valve. Unfortunately, ideal prosthetics don’t currently exist because necessary components such as the sewing ring, hinge points, occluders, struts, etc., all decrease the effective orifice area (EOA). The smaller the valve size, the greater a percentage of area these components take up. This creates the concern of implanting too small a valve, effectively creating an iatrogenic stenosis known as patient-prosthesis
mismatch (PPM). Although controversial, there is some evidence that if PPM is severe enough – particularly in the aortic position – it can lead to reduced exercise capacity and increased long term mortality.\textsuperscript{5,6}

The most effective predictor of PPM is the prosthetic valve’s known EOA indexed to the patient’s body surface area (EOAi = EOA\textsubscript{valve} / BSA\textsubscript{patient}). Some PPM is expected if the EOAi < 0.85 cm\textsuperscript{2}/m\textsuperscript{2} and severe PPM is generally defined as EOAi < 0.65 cm\textsuperscript{2}/m\textsuperscript{2}. Manufacturers typically include the valve’s EOA in the package insert, as well as the recommended valve size for a given patient BSA. Table 1 lists the reported EOAs for common valve models and sizes used in the aortic position. As a general rule, mechanical valves have higher EOAs than stented bioprosthetics for any given size.

**Table 1: Expected EOAs (cm\textsuperscript{2}) of common prosthetic aortic valves\textsuperscript{4}**

<table>
<thead>
<tr>
<th>Valve Model</th>
<th>19 mm</th>
<th>21 mm</th>
<th>23 mm</th>
<th>25 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbomedics (bileaf mech)</td>
<td>1.06</td>
<td>1.41</td>
<td>1.75</td>
<td>2.19</td>
</tr>
<tr>
<td>On-X (bileaf mech)</td>
<td>1.50</td>
<td>1.70</td>
<td>2.00</td>
<td>2.40</td>
</tr>
<tr>
<td>St. Jude Regent (bileaf mec)</td>
<td>1.84</td>
<td>2.47</td>
<td>2.91</td>
<td>3.34</td>
</tr>
<tr>
<td>CE Perimount (stent bio)</td>
<td>1.22</td>
<td>1.82</td>
<td>1.96</td>
<td>2.12</td>
</tr>
<tr>
<td>Medtronic Mosaic (stent bio)</td>
<td>1.02</td>
<td>1.13</td>
<td>1.56</td>
<td>1.80</td>
</tr>
</tbody>
</table>

As can be seen from Table 1, it may be difficult to obtain an EOAi > 0.85 cm\textsuperscript{2}/m\textsuperscript{2} when using small size valves, particularly stented bioprosthetics. One way surgeons can deal with this problem is by performing an aortic root enlargement (i.e. a Manouguian procedure) to allow for placement of a larger size valve. This approach comes with the price of increasing potential operative complications. Stentless bioprosthetics may offer another option. They typically have EOAs in the range of bileaflet mechanical valves, but offer the advantage of being able to place a larger valve for any given annulus size.

**Case Conclusion**

Getting back to the patient in the original discussion, there are several likely explanations for the high peak gradient obtained following her valve replacement. The most important concern, of course, would be to rule out significant obstruction and possible prosthetic valve dysfunction. According to the 2D examination performed, all valve leaflets were visualized to be moving well and the valve annulus appeared stable. Given the normal 2D interrogation, it is unlikely that valve dysfunction exists. At 60 inches tall and 50 kg, the patient has a calculated BSA of 1.4 m\textsuperscript{2}. Assuming the #19 bioprosthetic valve inserted was a CE Perimount (EOA = 1.22 cm\textsuperscript{2}), the EOAi is 0.87 cm\textsuperscript{2}/m\textsuperscript{2} and significant PPM is also unlikely.
Instead of valve dysfunction or PPM, the cause of the high gradient is likely due to misuse of the simplified Bernoulli equation. Because of the inotropes and the post-CPB state, the flow through the left ventricular outflow tract cannot be assumed to be negligible. The complete Bernoulli equation should be used to calculate a peak gradient. However, it should still be recognized that the patient is in a hyper-dynamic state and the gradient obtained in the OR will likely be significantly lower in a few days. A better way to use spectral Doppler to screen for obstruction would be to obtain a mean gradient. In the aortic position, mean gradients less than 20 mmHg should be expected. Higher numbers should signal the examiner to take a closer look with 2D imaging.

Summary

- Gradients via CW Doppler differ from those obtained by cardiac catheterization
- Use the complete Bernoulli equation for peak gradients post valve replacement
- Hyper-dynamic states ↑ gradients – they will likely be lower post-op
- Consider the possibility of PPM in small patients – obtain EOAi pre-op
- Valve dysfunction is unlikely if the 2D examination is normal


