A dilution curve is produced by an injection of non-diffusible indicator (isotonic saline) into a central vein (including femoral). The shape of the curve reflects the route that blood takes through the chambers of the heart and the lungs. The presence of intra-cardiac shunts or shunts external to the heart, such as a PDA alters the normal route of cardiopulmonary blood passage and, consequently, changes the shape of the dilution curve [1]. Characteristic features of the dilution curve that are used to identify shunts include:

a. Appearance time (Ta): time from the beginning of the venous injection to the beginning of the dilution curve (Fig.1)

b. Asymmetry of the dilution curve shape, represented by the ratio of total curve horizon (b) and upslope of the horizon (a) at the half height R=b/a (Fig.1)

c. Abnormalities in the dilution curve such as a change in the upslope or a change in the shape of the peak

**Right-to-Left (R-L) Shunts**

An early indication of R-L shunting is a dilution curve that appears immediately upon indicator injection. This short appearance time (Ta) results when part of the indicator bypasses the lungs and travels directly to the peripheral recording site and is used to identify R-L shunts.

Another indication of R-L shunting is abnormalities in the shape of the curve such as a bump in the upslope (Fig. 2) or a curve with dual peaks (Fig. 3). Mathematical models and references [1, 2] suggest that the area under the upslope bump is proportional to the shunt size (relatively small shunting Qp/Qs* = 0.8 - 0.9), while dual peaks suggest that a larger portion of blood is bypassing the lungs (Qp/Qs* = 0.4 - 0.7). When a curve does not exhibit obvious abnormalities or where the shunt fraction is less than 10%, the value of Qp/Qs is not displayed on the COstatus® monitor.

**LIMITATIONS: RIGHT-TO-LEFT SHUNT IDENTIFICATION**

For calculation of the appearance time (Fig.1), the software automatically subtracts the travel time of the indicator in the arterial extension line, assuming its priming volume is around 0.5 ml. A large priming volume of the arterial extension (0.6 ml+), may lead to missing the identification of a R-L shunt. In cases where there is no extension line, the R-L shunt message can be erroneous. The Qp/Qs* estimation ratio can only be applied to patients with hearts that have all four chambers and cannot be applied to conditions such as single ventricle physiology.
Shunt Evaluation Software cont.

Left to Right (L-R) Shunts

Increased asymmetry of a dilution curve is known to be a sign of the presence of L-R shunt Fig.4 [1, 2]. The first portion of indicator travels in a normal fashion and forms the upslope portion of the dilution curve. The second part of the indicator recirculates through part of the cardiopulmonary system before reaching the sensor. This part forms an asymmetrical down slope of the dilution curve. Quantity assessment of Qp/Qs* is based on a mathematical model of proportionality of increased asymmetry of dilution curve and an increase of left to right shunt flow.

LIMITATIONS: LEFT-TO-RIGHT SHUNT IDENTIFICATION

a) In rare cases the asymmetry of the curve (small Qp/Qs=1.1-1.4), may be associated with a moderate or large regurgitation [3]. For large Qp/Qs values, the probability that it is caused by regurgitation is minimal.***

b) In rare cases the asymmetry of the curve (small Qp/Qs= 1.1-1.4) may be caused by substantial asymmetry in lung perfusion [4,5]. This was noted in cases after successful surgery for total or partial anomalous pulmonary venous return and transposition of great vessels.***

c) Long injection time: curve noise may compromise the quality of L-R shunt identification. For an injection time exceeding 10 cardio cycles a “?” sign will appear before the Qp/Qs value. When the injection time exceeds 15 cardio cycles, or in cases of “Noisy baseline” message, no shunt identification will be performed.

Bidirectional Shunts

The presence dilution curve abnormalities that include an early appearance time and asymmetrical structure may suggest shunt flow in both directions (Fig. 5). This may indicate bidirectional flow through some anatomical defect, or the presence of at least two anatomical shunts, for example, an intra cardiac-shunt and a PDA. In the case of a bidirectional shunt the displayed Qp/Qs value is a fraction of the oxygenated blood (blood that passed through the lungs). Limitations for L-R and R-L shunts are also applicable to bidirectional shunts.

*** The Qp/Qs* value displayed in these cases will show the magnitude of the curve asymmetry. The tendency of the Qp/Qs* value during treatment to move to 1 (one) will indicate that the cardio-pulmonary circulation is getting closer to circulation observed in patients with normal lungs and no shunt defects.
Interpretation of Hemodynamic Data

1. Cardiac Output and related CI values always represent the output of the left ventricle into the aorta (systemic blood flow).
2. Central Blood Volume (CBV) and Active Circulation Volume (ACV) are correctly calculated regardless the presence or absence of shunts.
3. Total End Diastolic Volume (TEDV) and Total Ejection Fraction (TEF) are not calculated for shunt patients.
4. Hemodynamic results during a measurement session may be less reproducible as patient hemodynamics increasingly depends on pressure gradients, including breathing variations.
5. Due to hemodynamic variability, shunt identification and Qp/Qs* may vary between measurement sessions and within a measurement session.

Accuracy of Shunt Identification: Sensitivity and False Positives

Calculation of sensitivity and false positive values was based on a pediatric data archive of 2643 dilution curves from 341 patients. The conformation or non conformation of the presence or absence of shunts was based on Echo and Cath lab evaluation reported by a physician. All curves were visually examined and compared with results of the software calculations and the physician’s report. Based on the data archive and publications, the current algorithm is expected to have sensitivity for shunt identification in the range of 87.5-98% and false positives in the range of 2 - 4% (assuming that ECHO and Cath Lab data is 100% accurate).

Estimation of Qp/Qs Values

RIGHT-TO LEFT-SHUNT:
Quantity assessment of Qp/Qs*± SD is based on a mathematical model of proportionality of increased asymmetry of a dilution curve and an increase of left to right shunt flow. This approach was explored and validated in early papers [1, 2, 6, 7] where dye indicators were used. The value of SD represents the variation of asymmetry of the dilution curve due to other factors not related to shunting, such as the rate of injection, accuracy of the algorithm to calculate area, deviation of curve asymmetry due to other hemodynamic factors. Based on a pediatric data archive of 1094 non-shunt curves, the input of these factors on asymmetry is 13% of Qp/Qs value (one SD).

RIGHT-TO LEFT-SHUNT:
Quantity assessment of Qp/Qs* is based on a mathematical model of proportionality of the observed area under the upslope bump (Fig. 2a) or the first part of the dilution curve with two maximum peaks (Fig. 2b). This approach was also explored in early papers [1,2] where dye indicators were used. The value of SD is 15% of Qp/Qs and is increased versus L-R shunt due to the larger uncertainty in area calculation.

BIDIRECTIONAL SHUNT
Quantity assessment of Qp/Qs* is the same as for R-L shunt. The displayed value of Qp/Qs is a fraction of the oxygenated blood (blood that has passed through the lungs).

REFERENCES