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Introduction

Stroke Volume (SV, see Eq. 1) is a measurement of cardiac function related to ventricular performance in clinical and rodent research applications. SV measures the volume of blood ejected with each contraction [1]. The gold-standard non-invasive way to obtain SV is through extraction of right ventricle (RV) and left ventricle (LV) volume measurements from cardiac magnetic resonance (CMR) imaging data (see Fig. 1) [2].

$$\text{Stroke Volume} = \text{End Diastolic Volume} - \text{End Systolic Volume} \quad \text{Eq. 1}$$

A typical CMR image includes multiple short-axis (SA) slices (see Fig. 1a) acquired along the length of the heart and a single long-axis (LA) slice where both ventricles are visible (see Fig. 1b) [2]. SV estimation relies on the manual delineation of SA slices, so the accuracy of a volume calculation is limited by the number and coverage of SA slices. In some cases, particularly in rodent CMR images, the standard 5 SA slices fail to cover the entire base-to-apex span (see Fig. 1c). We propose that omitted volume and an erroneous SV results due to these imaging limitations.

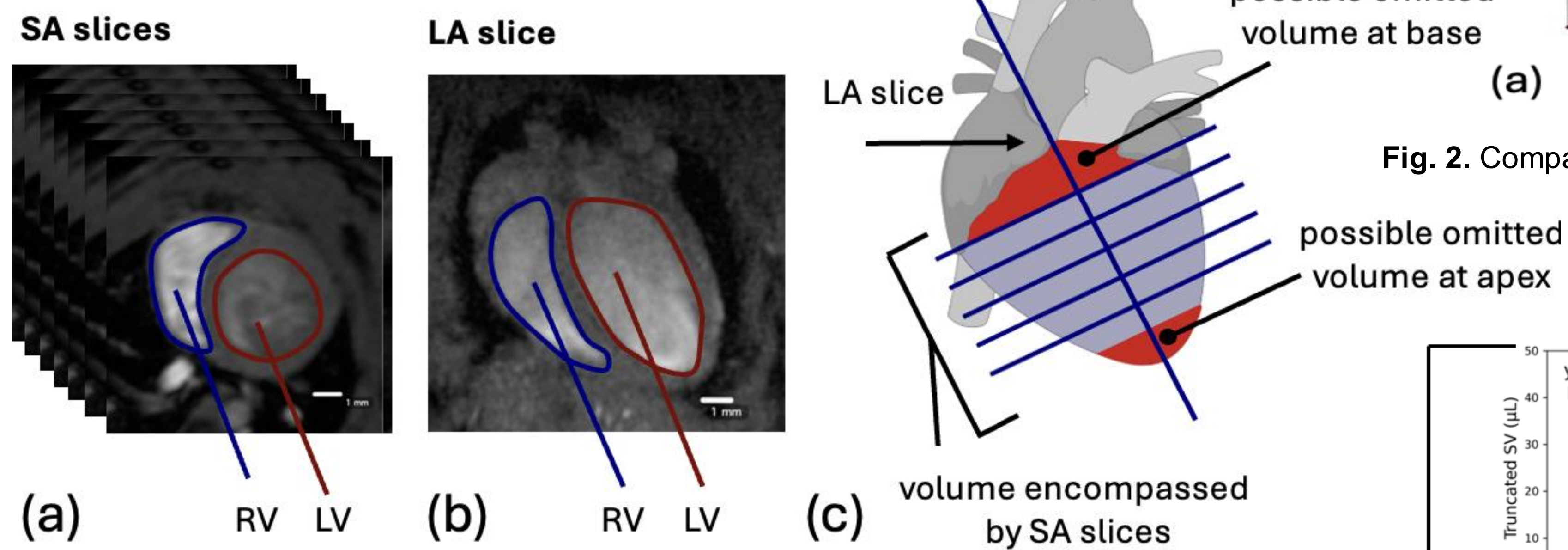


Fig. 1. Rodent CMR volume estimation uses manual delineations from a stack of (a) SA slices and (b) a LA slice orthogonal to the SA stack. (c) The LA highlights volume that may be omitted (red) due to limited SA coverage [3].

Methods

- CMR Acquisition:** Balanced steady state free precession (bSSFP) cine CMR was acquired in 9 mice: N = 5 at 7-weeks after Sham surgery (control) and N = 4 at 7-weeks after Pulmonary Artery Banded (PAB) surgery. Of 9 LV and RV scans, 4 scans (3 RV, 1 LV) were excluded due to subject movement disrupting acquisition.
- Segmentation:** CMR segmentation involved the manual endocardium delineation of the 7 available SA slices and one LA slice [4]. Inter-observer variability showed acceptable agreement (ICC = 0.941).
- SA α -shape estimation:** Each SA slice was aligned parallel to the x-y plane and stacked from the apex to the base along the z-axis (see Fig. 2b). An α -shape was created from the the 80 coordinates along the circumference of each SA slice.
- LA + SA α -shape estimation:** After applying model realignment (described in SA α) shape-preserving piecewise cubic interpolation was used to create a 3D point cloud (See Fig. 2c). An α -shape was then created from the resulting point cloud.
- Numerical Volume Calculation of an α -shape:** We utilized a Monte Carlo technique that randomly assigns the domain $1e6$ points while tracking the number of points that landed within the α -shape. The ratio of points that landed within the α -shape to the total number of points is directly proportional to the cavity volume (software: MATLAB, MathWorks, MA).
- Statistical Analysis:** We performed correlation and Bland-Altman analysis for SV between non-truncated (using all 7 SA slices) and truncated (omitting the most apical and basal slice) images.

Objective and Hypothesis

Objective: Evaluate the performance of three volume estimation methods under constrained CMR data (5 SA slices) by comparing estimates to baseline volumes derived from full coverage (7 SA slices).

- Simpson’s Disk Summation (SD)** [4]: This is a well-established algorithm used in most commercial software. Cavity volume is calculated by multiplying the area within the delineated contour by the slice thickness (see Fig. 2a).
- SA α -shape estimation (SA α)**: Estimates cavity volume by fitting an α -shape to the delineated contours from SA slices (see Fig. 2b)
- LA + SA α -shape estimation (LA+SA α)**: Combines one LA and all available SA slices for volume estimation (see Fig. 2c).

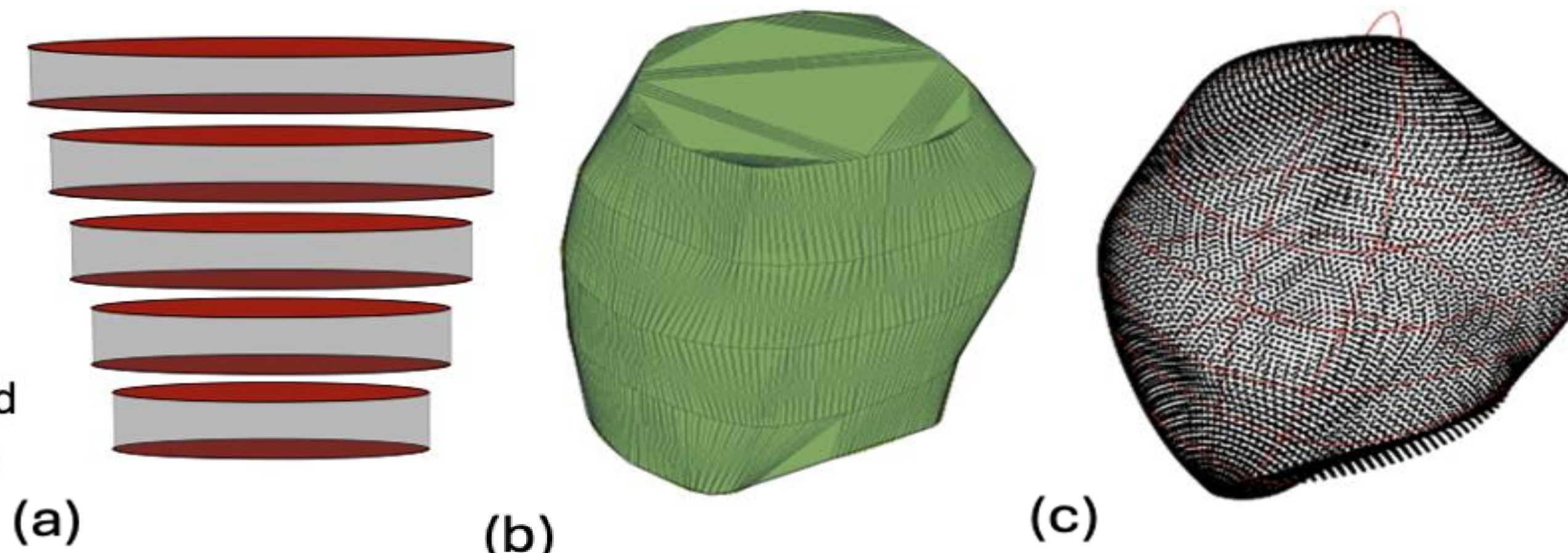


Fig. 2. Compared methods for cavity volume calculation: (a) SD; (b) SA α ; (c) LA+SA α .

Results

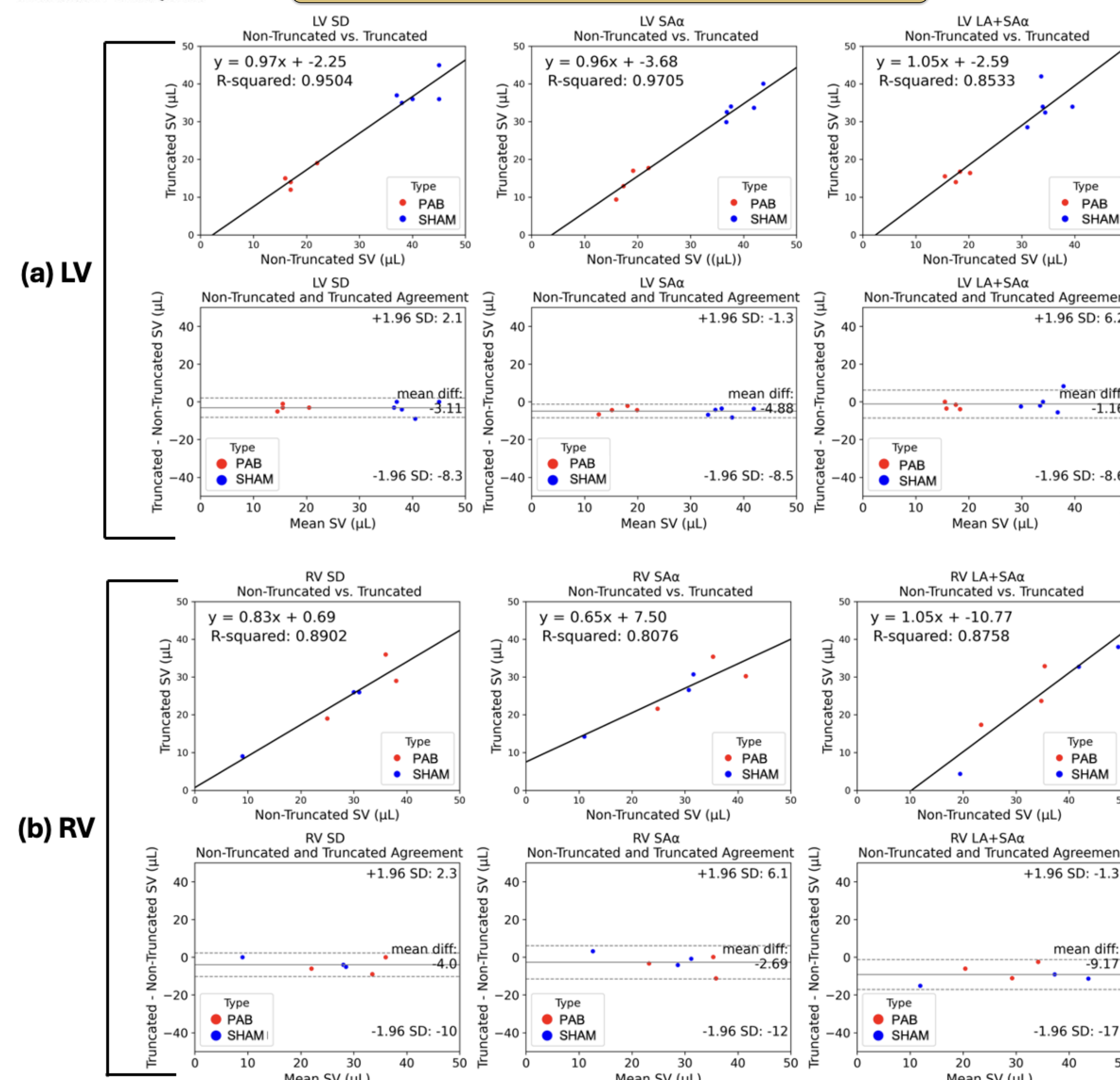


Fig. 3. Linear regression and Bland-Altman analysis of Non-Truncated vs. Truncated SV for (a) LV and (b) RV using three volume estimation methods.

Conclusions

- Truncating SA slices from 7 to 5 resulted in the consistent underestimation of SV across all methods. Mean differences ranged from $-1.16 \mu\text{L}$ (LV LA+SA α) to $-9.17 \mu\text{L}$ (RV LA+SA α), with the largest discrepancies seen in the RV.
- The SD method integrates area using Euler’s method (error $\sim h$) and showed the most consistent underestimation of volumes, likely due to geometric assumptions and limited apical/basal context.
- SA α made various improvements in LV/RV by reconstructing a continuous surface (error $\sim h^2$), reducing mean differences in RV and SD in LV. This resulted in the lowest mean difference in the RV.
- LA+SA α provided additional context and achieved closest proportional agreements in LV/RV with the overall lowest mean difference (LV LA+SA α – $1.16 \mu\text{L}$) and a regression slope closest to 1 ($m = 1.05$, RV/LV LA+SA α).
- Discrepancies were more pronounced in the RV, which has a more complex geometry and is more difficult to capture in standard CMR acquisition. While LA+SA α improved regression slope (1.05) and maintained a strong explanation of variability r^2 (0.8758), the mean difference remained high ($-9.17 \mu\text{L}$), highlighting the complexity of RV volume estimation and possible misalignment of CMR views.

Future Research

- We plan to validate CMR-derived stroke volumes by cross-referencing with ex vivo CT-based cardiac volumes.
- We also aim to implement machine learning for automated segmentation to reduce inter-observer variability and improve processing speed.
- A larger dataset is needed to better evaluate volume estimation methods under truncation, as the current sample size limits generalizability.
- Rodent CMR is constrained by motion artifacts and anesthesia limits. Exploring additional CMR views and tradeoffs may improve LA+SA α accuracy.

References

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