Assessing the role of heart morphology in determining cardiac functionality in Atlantic salmon (*Salmo salar* L.)

Victoria Becker[1,2], Simona Kavaliauskiene[3], Daniel Morgenroth[1,2], Sudip Mahat[3], William E. Louch[1,2], Ida Beitnes Johansen[3], Michael Frisk[1,2]

[1]Institute for Experimental Medical Research, University of Oslo and Oslo University Hospital Ullevål, Oslo, Norway

[2]K.G. Jebsen Center for Cardiac Research, University of Oslo, Oslo, Norway

[3]Department of Preclinical Sciences and Pathology, Faculty of Veterinary Medicine, Norwegian University of Life Sciences, 369 Oslo, Norway.

INTRODUCTION

Deviating cardiac morphology is prevalent in farmed Atlantic salmon hearts. These morphological deviations have been linked to mortality during handling, transportation, and delousing events (Poppe et al., 2003, Engdal et al., 2024). Heart morphology and function are likely intertwined but no studies have examined how cardiac morphological deviations affect function directly in Atlantic salmon.

Here, we hypothesised that deviating heart morphology affects both systolic and diastolic function and that the number of morphological traits exhibited by the individual heart exacerbates the functional response.

MATERIAL & METHOD

172 Atlantic salmon (size range = 150 - 12250g) were sampled in full salinity salt water. The fish included were from a variety of husbandry backgrounds (rearing and breeding), including aquaculture, wild, and experimental fish.

Heart morphology was examined qualitatively in excised hearts using the methods described by Engdal et al. 2024 (Fig. 1). Prior, in vivo echocardiography was used to assess cardiac function as described by Becker et al. 2024 (Fig. 2) and intraventricular blood pressure was measured in a subset of fish. Based on the qualitative analysis fish were grouped into wild-type (WT) and deviating-type (DT) hearts. All data is presented as median with 95 % confidence intervals. Sample sizes, after outlier analyses, are marked on each graph bar. P ≤ 0.05 was considered statistically significant.

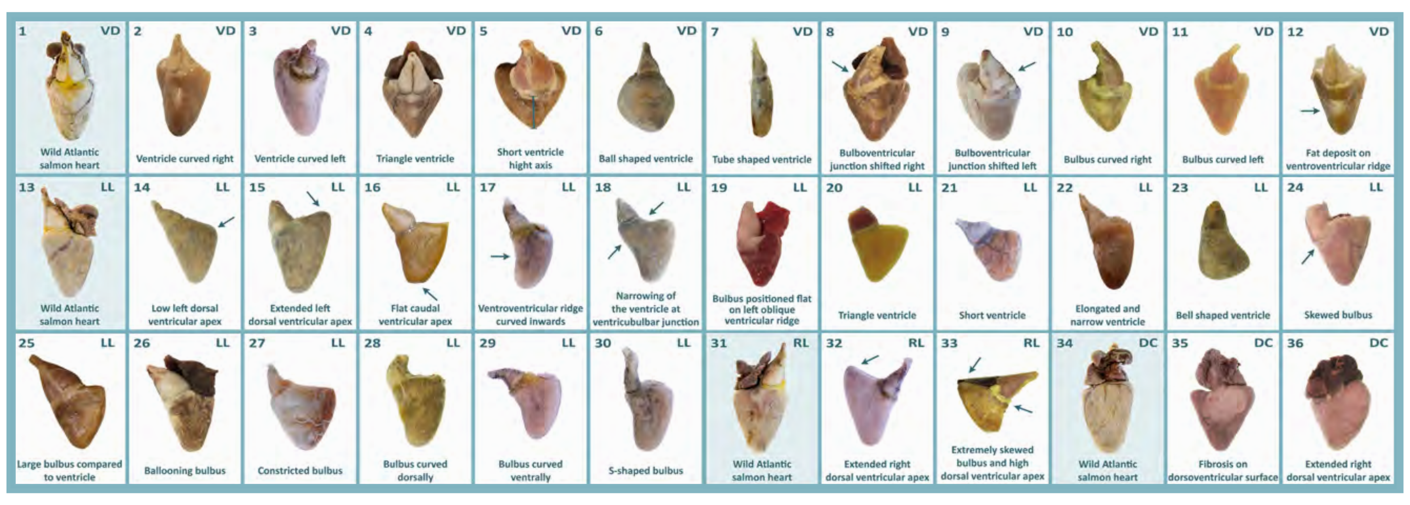


Figure 1. Qualitative assesment of cardiac morhpology in Atlantic salmon. Morphology examples in four different projections: ventrodorsal (VD), left lateral (LL), right lateral (RL) or dorsocranial (DC). Wild type hearts (WT) are depicted in panel 1, 13 , 31 and 34. All other represent deviating hearts. Modified from Engdal et al. 2024.

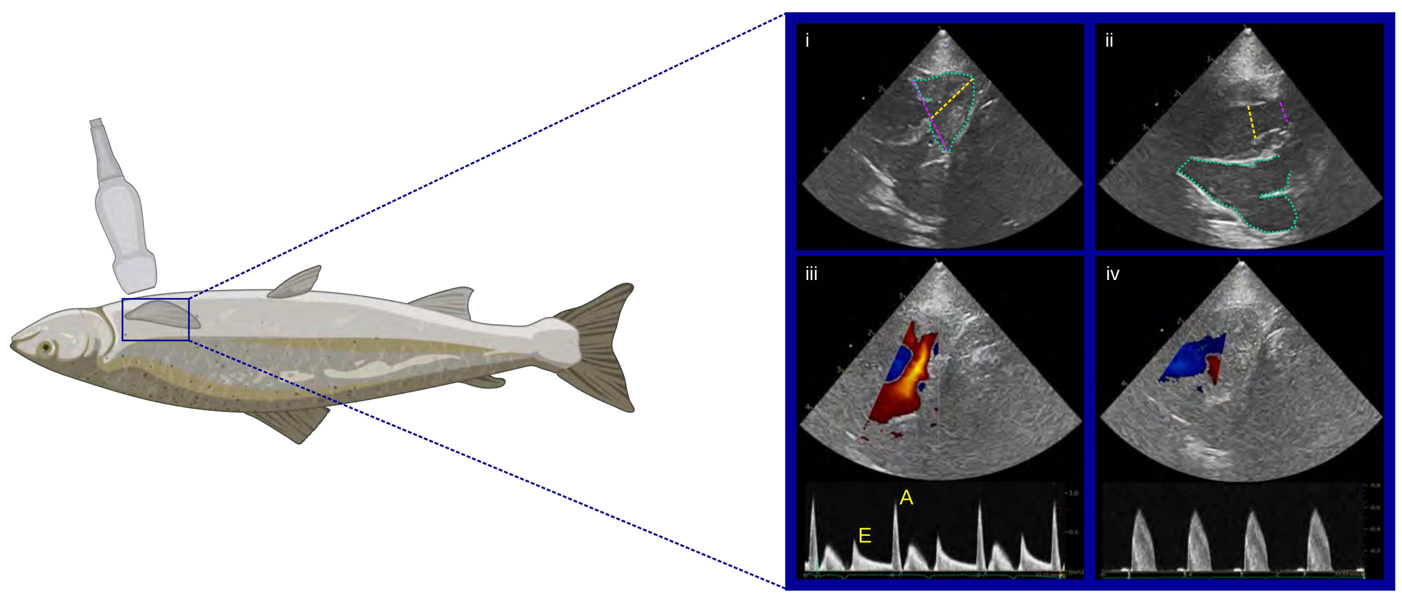
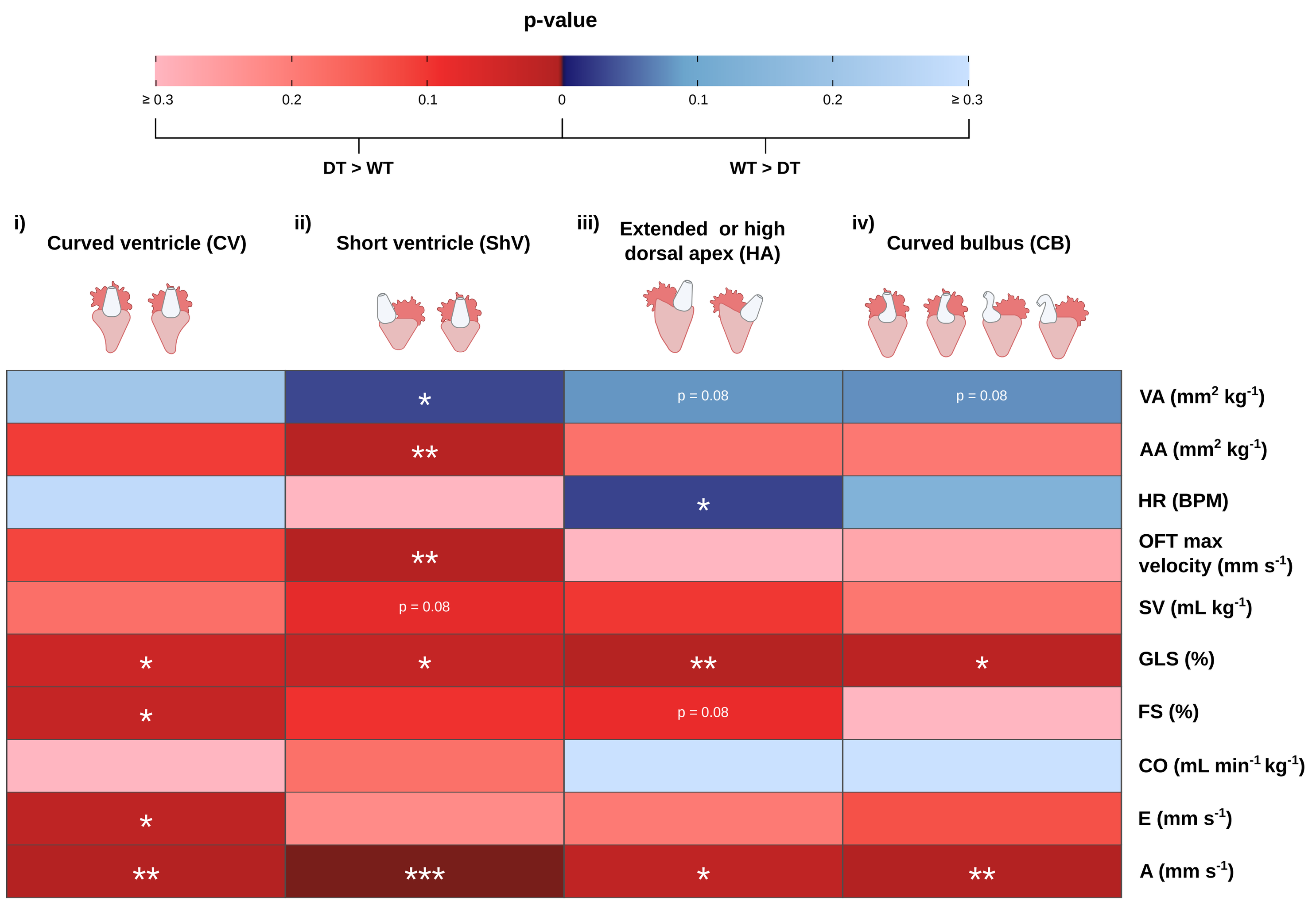


Figure 2. Echocardiography was used to evaluate heart function. (i) Ventricular dimensions, including ventricle length (yellow), height (ventral-dorsal height) (purple), and ventricular area (green). (ii) Recording of bulbus and atrium with depiction of bulbo-ventricular (BV) valve diameter (purple), outflow tract (OFT) diameter (yellow) and atrial area dimensions (green). (iii) Early (E) and late (A) diastolic blood flow velocities, (iv) Systolic haemodynamics (ventricular outflow tract).



Becker, V., Kavaliauskiene, S., Sandblom, E., Zena, L.A., Gräns, A., Louch, W.E., Sjaastad, I., Johansen, I.B. and Frisk, M., 2024. Echocardiography-a non-invasive alternative for assessing cardiac morphology and function in Atlantic salmon (Salmo salar L.). Aquaculture, p.741223.

Engdal, V. A., Dalum, A. S., Kryvi, H., Frisk, M., Torsvik, H., Hodne, K., Romstad, H. & Johansen, I. B. 2024. State of the heart: Anatomical annotation and assessment of morphological cardiac variation in Atlantic salmon (Salmo salar L.). Aquaculture, 578, 740046.

Poppe, T. T., Johansen, R., Gunnes, G. & Tørud, B. 2003. Heart morphology in wild and farmed Atlantic salmon Salmo salar and rainbow trout Oncorhynchus mykiss. Diseases of Aquatic Organisms, 57, 103-108.

RESULTS

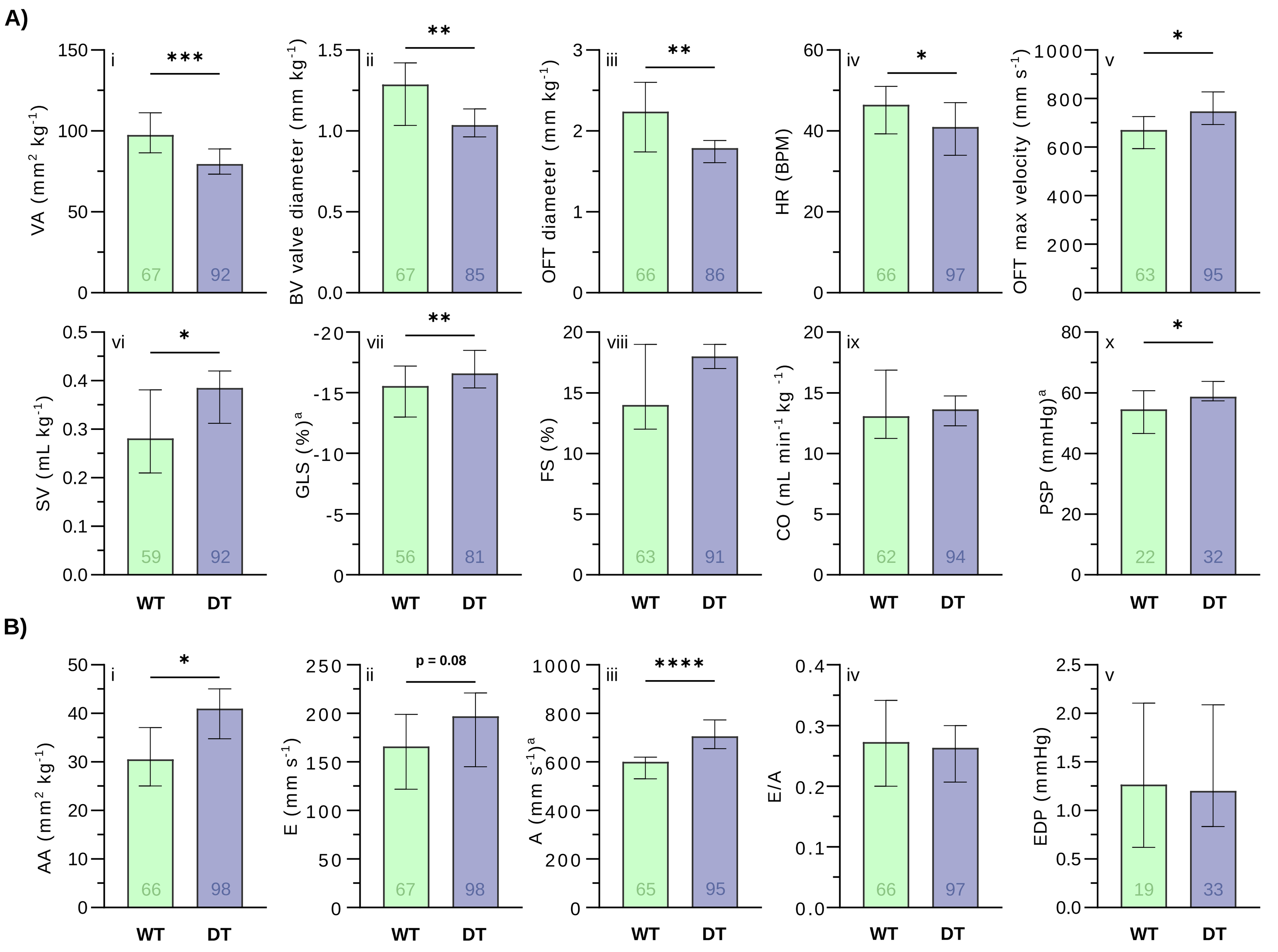


Figure 3. Deviating morphology is associated with altered systolic and diastolic function. (A) Deviating cardiac morphology (DT) is associated with smaller ventricular area (VA, i), bulbo-ventricular (BV) valve diameter (ii) and out flow tract (OFT) diameter (iii). DT hearts present with lower heart rate (HR, iv), increased OFT max velocity (v), stroke volume (SV, vi) and contractility (vii). No change was observed for fractional shortening (FS, viii) nor cardiac output (CO, ix). Peak intraventricular systolic pressure (PSP) was increased in fish with DT hearts (x). **(B)** DT hearts had (i) relatively larger atria (AA), and accelerated late (A) diastolic blood flow velocities (iv, v). End diastolic intraventricular pressure (EDP) was similar between groups. All statistical comparisons are non-parametric unless the left y-axis legend is marked with a.

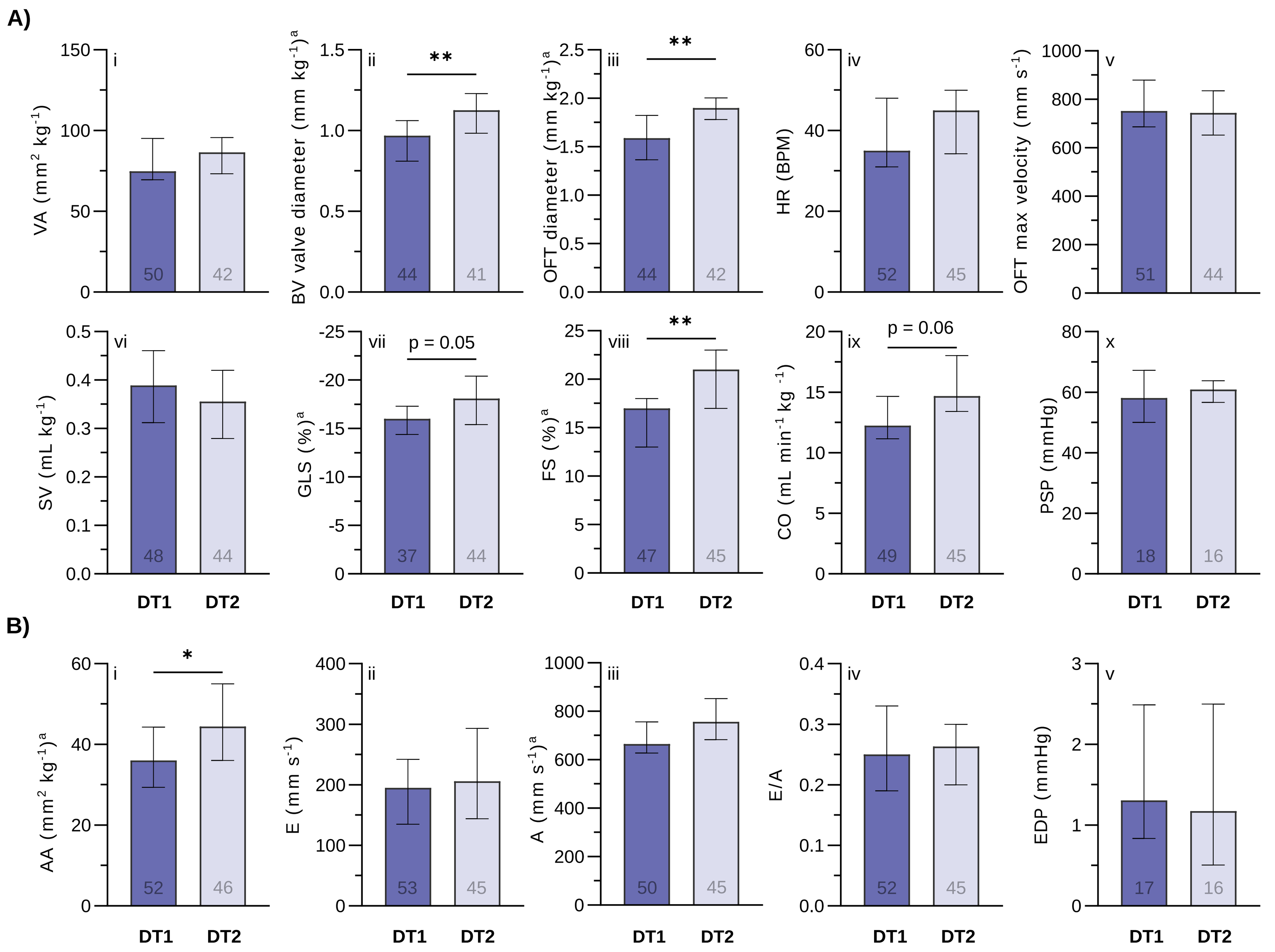


Figure 4. Number of morphological deviations impacts systolic and diastolic parameters. Comparison between hearts exhibiting one deviating morphological trait (DT1), and two or more (DT2). (A) (i) No differences were found for Ventricular area (VA). (ii) Bulbo-ventricular (BV) valve and (iii) outflow tract (OFT) diameter are larger in group DT2. DT1 and DT2 shows similar (iv) heart rate (HR), (v) OFT max velocity and (vi) stroke volume (SV). Cardiac contractility (vii) (global longitudinal strain (GLS)) and (viii) fractional shortening (FS) were elevated in the DT2 group. (ix) Cardiac output (CO) and (x) peak intraventricular systolic pressure (PSP) were not affected. (B) (i) Atrial area (AA) are larger in the DT2 group, with no differences in neither (ii) early (E) or (iii) late (A) diastolic velocity, as well as (iv) E:A ratio and (v) end-diastolic intraventricular pressure (EDP). All statistical comparisons are non-parametric unless the left y-axis legend is marked with a

Figure 5. Specific deviating cardiac traits affect cardiac function distinctly. WT hearts were compared with the most prevalent individual deviating cardiac traits (DT). (i) Curved ventricles (CV, i), short ventricle (ShV, ii), Extended or high dorsal apex (HA, iii), and those with curved bulbi (CB, iv). Colour bar indicates p-values: Red = DT function is higher than WT. Blue = DT function is lower than WT. We observed that ShV was the only deviation resulting in a smaller ventricular area (VA) and larger atria (AA). HA was the only trait presenting with lowered heart rate (HR). Outflow tract (OFT) max velocity was only changed in ShV. However, all DT's presented with increased contractility i.e. global longitudinal strain (GLS). Despite hypercontractility, no changes were found for cardiac output (CO). All DT hearts showed increased late diastolic velocity (A), though only CV hearts showed increase in early diastolic velocity (E).

CONCLUSION

We observed that deviating heart morphology is associated with altered cardiac function, primarily, lowered heart rate concurrent with accelerated hemodynamics and increased contractility. Likely, these alterations serve to maintain cardiac output at rest. Specific deviating traits have differing impact on cardiac function. Key parameters such as enlarged atrium and elevated diastolic and systolic blood flow velocities, were found to be altered in deviating traits (curved and short ventricles) which have previously been associated with mortality. Suggesting that these parameters are important functional measurements for evaluation of cardiac health.