ETH zürich

Effects of Pulse Duplicator Designs on Valve Behavior

Caroline Smid[1], Georgios Pappas[1], Volkmar Falk[2,3,4], Nikola Cesarovic[2,3], and Paolo Ermanni[1]
[1]Laboratory of Composite Materials and Adaptive Structures, ETH Zürich; [2]Translational Cardiovascular Technologies, ETH Zürich; [3]Klinik für Herz-, Thorax- und Gefäßchirurgie; [4]Deutsches Herzzentrum Berlin, Klinik für Kardiovaskuläre Chirurgie, Charité Universitätsmedizin Berlin, Germany

1 Motivation

- A perfect implantable valve that is satisfying both hemodynamic and durability requirements is still not found [1]
- This study is in the framework of developing a **fully-polymeric transcatheter heart valve** aiming to fulfill both requirements
- A pulse duplicator is needed to conduct the characterization of novel heart valve designs under physiological conditions

2 Methods of parametric study and evaluation

Objective

- Create an **accurate** simulator of the entire **cardiac cycle** for valve assessment and design optimization
- Valve exposure to physiological pressure differential (ΔP) & flow environment for all heart valves

Main challenge

- Pulse duplicator components can have a strong influence on pressure history & flow details

Parametric study: Effects of hemodynamic conditions and design

- Reference pulse duplicator with bioprosthetic valve in aortic and mitral position (Fig. 1)
- Physiological and pathological hemodynamic settings (Table 1)
- Components altered: compliance chamber (Ⓐ absence & Ⓑ air pressure), Ⓒ aortic resistance inducer, Ⓓ mechanical valve in mitral position, but also Ⓔ presence of endoscope apparatus

	Pressure condition [mmHg]	Heart rate [bpm]	Nominal cardiac output [l/min]
①	Normotensive (120/80)	70	5
②	Normotensive (120/80)	140	5
③	Normotensive (120/80)	140	10
④	Severe hypertensive (210/120)	70	5
⑤	Severe hypertensive (210/120)	140	10

Table 1: Five physiological and pathological hemodynamic settings

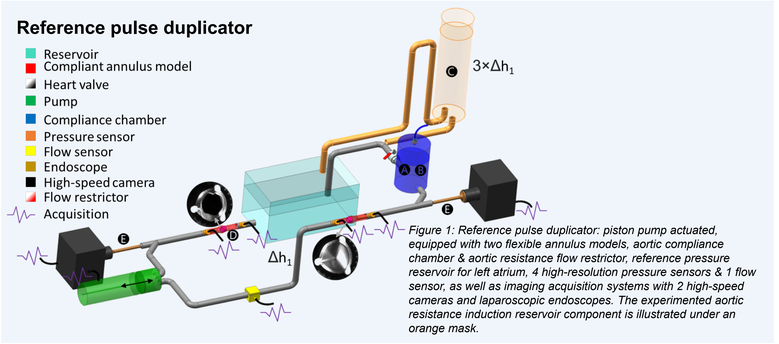


Figure 1: Reference pulse duplicator: piston pump actuated, equipped with two flexible annulus models, aortic compliance chamber & aortic resistance flow restrictor, reference pressure reservoir for left atrium, 4 high-resolution pressure sensors & 1 flow sensor, as well as imaging acquisition systems with 2 high-speed cameras and laparoscopic endoscopes. The experimented aortic resistance induction reservoir component is illustrated under an orange mask.

3 Results and Highlights

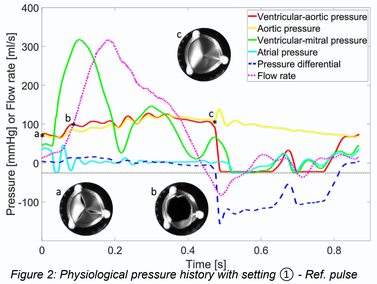


Figure 2: Physiological pressure history with setting ① - Ref. pulse duplicator

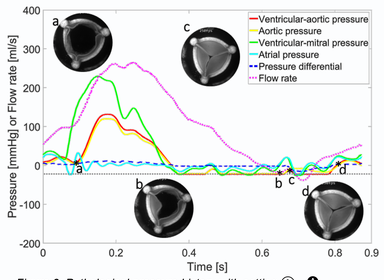


Figure 3: Pathological pressure history with setting ① - Ⓐ

- Absence of compliance chamber leads to
  - Aortic and ventricular-aortic pressure practically overlap. This can be attributed to the reduced flow resistance in the absence of the compliance chamber leading to lower ΔP.
  - A change in the wave propagation cannot be excluded
  - A lower regurgitation despite the increased cardiac output
- Late closing of mechanical valve leads to a very low actual cardiac output (same pump output), which is leading to a higher regurgitation & an apparent lower ΔP

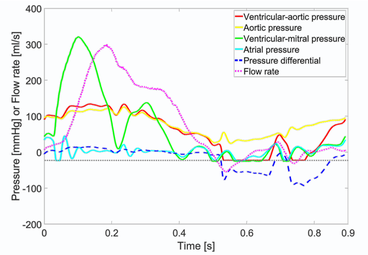


Figure 4: Physiological pressure history with setting ① - Ⓑ

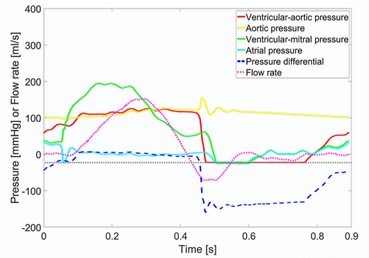


Figure 5: Physiological pressure history with setting ① - Ⓓ

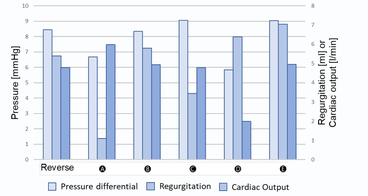


Figure 6: Pressure, regurgitation, and cardiac output with setting ① for each variation

Note that:
1. Nominal cardiac output is based on Ref. pulse duplicator, where true cardiac output was measured with the flow sensor
2. All history data are averaged over 10 cycles according to the ISO5840-3 [2]
3. The gray dashed line in the Figures 2 – 5 show the negative pressure limit that can be acquired with the pressure sensors
4. Pressure differential often referred as pressure gradient

4 Remarks

- High acquisition rate (~ 3.5 kHz) is needed to capture the phenomena [3,4]
- Fully-synchronized pressure, flow, and image acquisition is essential [5]

5 Conclusion

- Optimized set-up replicates a physiological and pathological valve environment in a robust manner
- Of paramount importance are: 1. compliance chamber, 2. flow restrictor as circulation pressure resistance. These are essential to maintain aortic and narrow pulse pressure. The less flow-disturbing pressure induction via reservoir is not sufficient to maintain the above characteristics, while the positive effect on the flow is minimal.
- Above mentioned characteristics can vary with valve type

References

1. Pibarot, P., & Dumesnil, J. G. (2009). Prosthetic heart valves: selection of the optimal prosthesis and long-term management. Circulation, 119(7), 1034–1048.
2. German Institute for Standardization. Cardiovascular implants - Cardiac valve prostheses. Part 3: Heart valve substitutes implanted by transcatheter techniques (2021).
3. Vennemann B, Rösgen T, Heinisch PP, Obrist D (2018). Leaflet Kinematics of Mechanical and Bioprosthetic Aortic Valve Prostheses. ASAIO J. 651-661.
4. Rodriguez RA, Dellimore KH, Müller JH (2019). Evaluating the Performance of Cardiac Pulse Duplicators Through the Concept of Fidelity. Cardiovasc Eng Technol. 423-436.
5. Jahren SE, Heinisch PP, Wirz J, Winkler BM, Carrel T, Obrist D (2015). Hemodynamic performance of Edwards Intuity valve in a compliant aortic root model. Annu Int Conf IEEE Eng Med Biol Soc. 3315-3318.

Partners:

Funding: This work was partially funded by the ETHeart initiative and the Zurich Heart project of Hochschulmedizin Zürich.