Supporting Information

A soft total artificial heart – first concept evaluation on a hybrid mock circulation

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Production of the soft artificial heart

The general production procedure of the artificial hearts was according to previously published work (reference 13 of the main manuscript). The mould of the artificial heart was designed using a computer aided design software (NX 8.5, Siemens, Germany) and 3D-printed in commercially available 3D-printers (HP Designjet 3D, Hewlett-Packard or uPrint SE Plus, Stratsys, both United States). The models were built of acrylonitrile butadiene styrene (ABS) with a support structure of polylactic acid (PLA). After the production of the mould, the PLA-support was dissolved in an alkaline bath and the resulting ABS mould was washed with water and dried in an airstream. The voids of the mould were filled with a mixture of room temperature vulcanizing (RTV) silicones (50 wt.% RTV 23 and 50 wt.% RTV 240, both Neukasil, Altropol, Germany). The corresponding amounts of monomer and cross-linker for both silicone types (RTV 23: 10 parts monomer, 3 parts cross-linker, RTV 240: 10 parts monomer, 1 part cross-linker) were weighted and mixed by hand. Before the silicone was filled into the voids, the mixture was degassed in a vacuum at 10 mbar for 15 minutes. The silicone was first cured over night at room temperature and then in an oven at 65 °C for 24 hours. After cooling down, the ABS mould was dissolved in an acetone bath until the whole ABS structure was removed. The resulting artificial heart made of a silicone monoblock was again dried in an oven at 65 °C for at least 24 hours. Mechanical heart valves with a diameter of 23 mm (Björk-Shiley type), surrounded by a ring of rubber, were placed in the in- and outlets to the ventricles and fixed by clamping with laces from the outside.

Geometry of the soft artificial heart

The approximated size of the sTAH and its chambers are depicted in Figures S1-S3 and Table S1. Figure S1 gives the sTAH as designed, while Figure S2 shows the geometry of the main body, which was designed using the form of the real human heart. Figure S3 gives the geometries of the chambers (left ventricle, right ventricle and expansion chamber). Tables S1 summarizes the volumetric data of the sTAH and its chambers, while Table S2 gives the minimum wall thicknesses between the chambers and the outer surface of the sTAH.

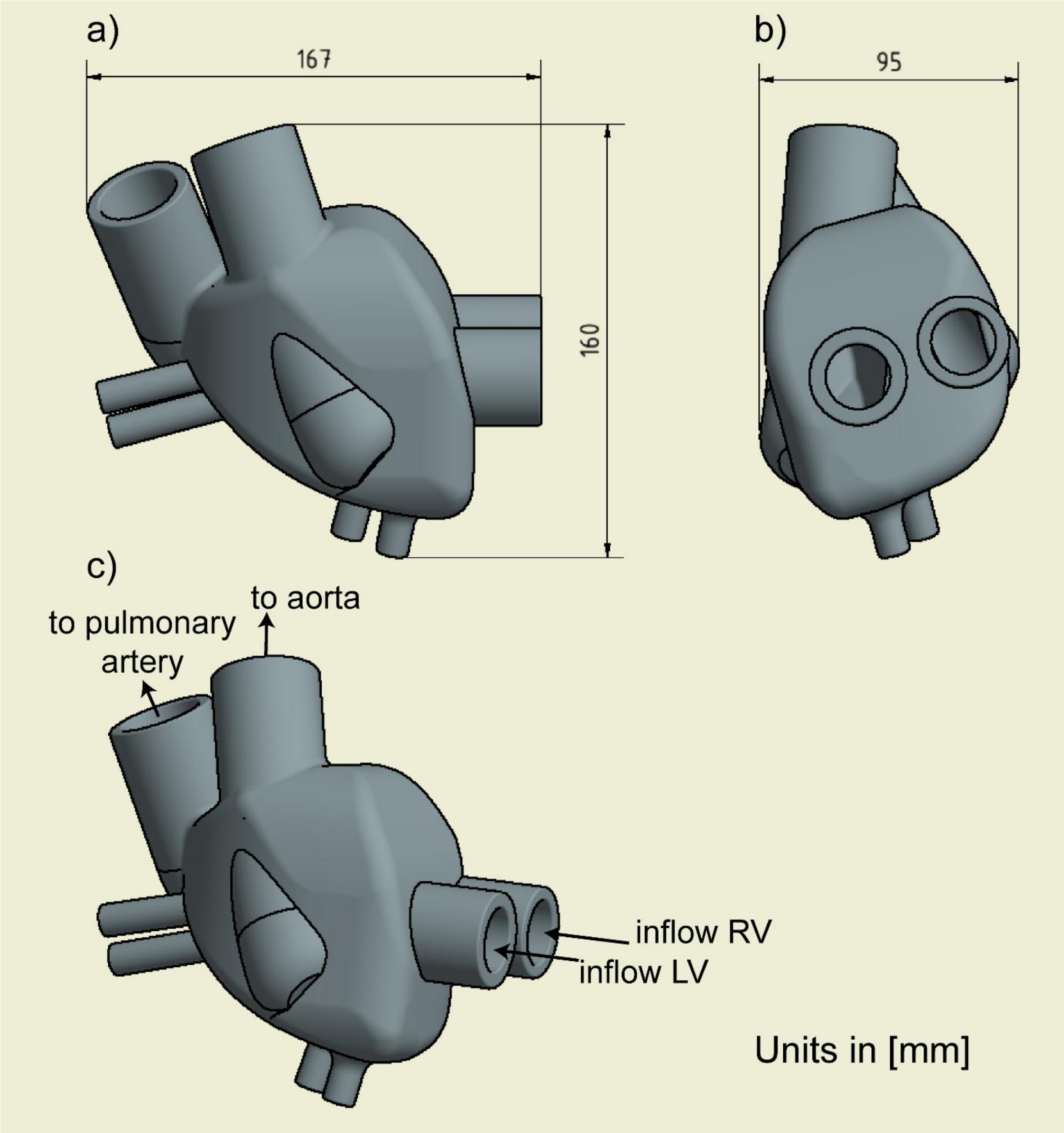

Figure S1. Sketch of the soft total artificial heart with its outer dimensions in millimetres. c) depicts the flow direction to and from the right ventricle (RV) and left ventricle (LV).

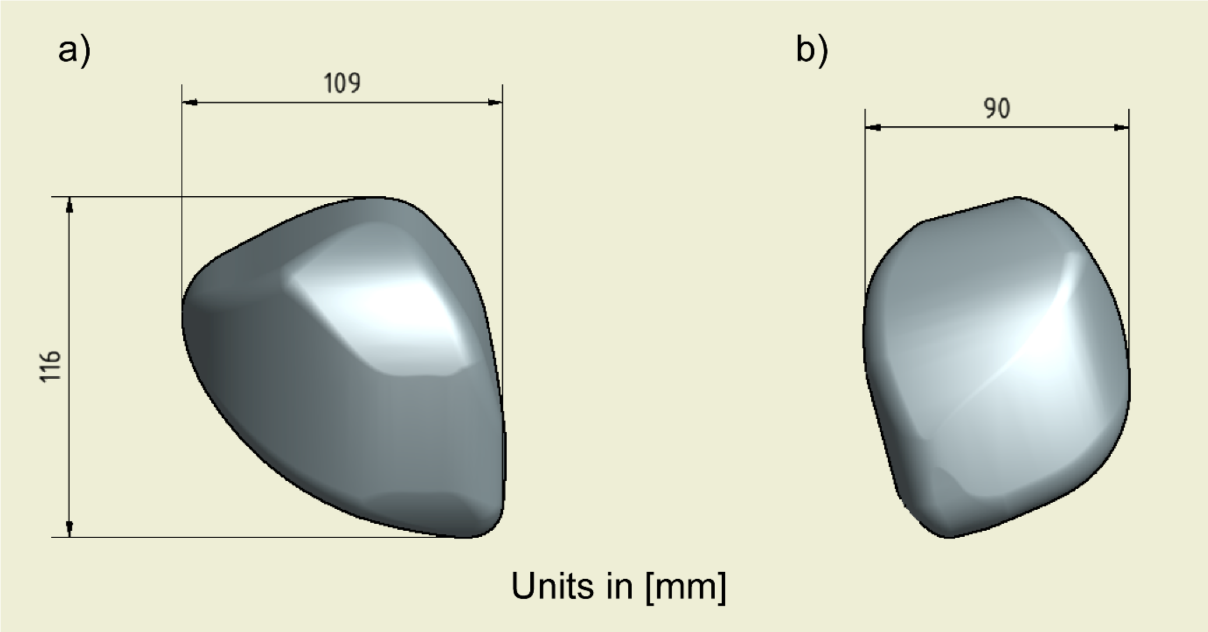

Figure S2. Sketch of the main body of the soft total artificial heart with dimensions in millimetres.

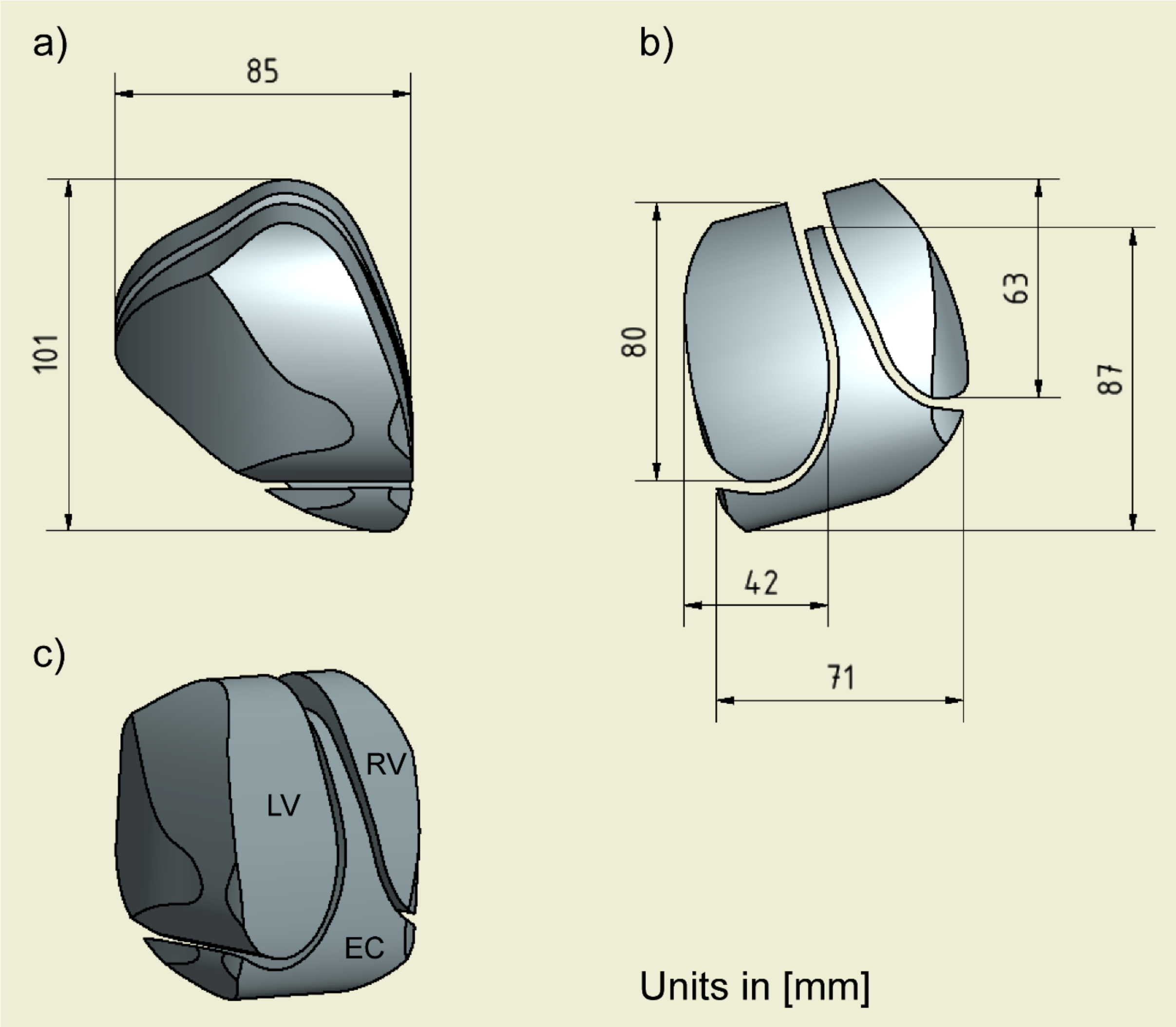

Figure S3. Sketch of the chambers of the soft total artificial heart with its outer dimensions in millimetres. LV, RV and EC are abbreviations for left ventricle, right ventricle and expansion chamber.

Table S1. Summary of the minimum wall thicknesses of the soft total artificial heart.

	wall thickness / mm
Outside – LV	3.6
LV – EC	2.3
EC – RV	2.8
RV – Outside	3.6
EC – Outside	4.1

Measurement of the tensile properties

The tensile properties of the silicone mixture was measured according to DIN 53504 norm. The sample size was 5. A Shimadzu Universal Testing Instrument AGS-X with a 10kN load cell was used.

The samples were produced by filling the degassed uncured silicone mixture into a mould and cured at 65 °C. The thickness of the samples were measured at three positions of the samples. The tensile tests were conducted with a pre-stress of 0.01 MPa and with a speed of 200 mm/min. The shore-A value of the material was measured three times using a Shore A Meter (LX-A, HANDPI). Figure S4 shows an exemplary stress-strain curve of the used silicone.

Table S2. Summary of the mechanical properties of the silicone elastomer mixture, which the sTAH is made of.

	Silicone elastomer mixture
Shore A Hardness	28 ± 1.2 (*n* = 3)
Tensile strength at break / MPa	1.82 ± 0.35 (*n* = 5)
Percent elongation at break / %	390 ± 60 (*n* = 5)
Elastic modulus / MPa	2.98 ± 0.16 (*n* = 5)

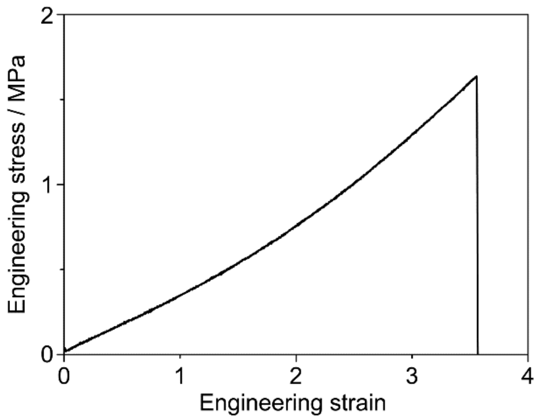

Figure S4. Typical stress-strain curve of the used silicone elastomer.

Actuation of the soft artificial heart

The pulsatile flow of the artificial heart was created by in- and deflating the expansion chamber between the two ventricles using pulses of pressurized air with the desired rate. A constant pressure of 2 bar was available from the house line. Three valves (VX245JEA, SMC, Japan) were used to control the pulses, one to control the inflow of the air (inflation) and two for the outflow (deflation). An illustration is given in Figure S5. The valves were controlled by a programmable logic controller (PLC). Table S3 gives the durations the valves are opened by the programme. The durations were chosen in a way that first, the desired heart rate was reached, second, the silicone did not rupture after one beat and third, the EC was able to relax/shrink to its initial state, before being inflated again. During inflation, valve 1 was opened for $t_{inflate}$, while valves 2 and 3 were closed. Once $t_{inflate}$ had passed, valve 1 was closed and valves 2 and 3 were opened for $t_{deflate}$. Afterwards, the cycle started again.

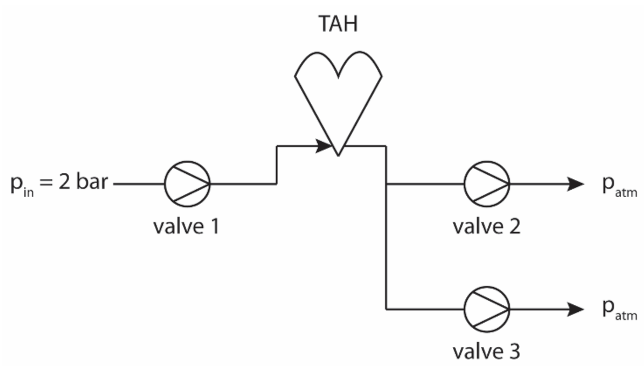

Figure S5. Scheme of the pneumatic actuation of the sTAH.

Table S3. Summary of the inflation and deflation times for different physiological heart rates. The times also correspond to the opening and closing times of the expansion chamber-controlling valves.

Heart rate / bpm	$t_{inflate}$ / s	$t_{deflate}$ / s
60	0.20	0.80
70	0.19	0.67
80	0.18	0.57
90	0.16	0.50
100	0.16	0.44
110	0.16	0.39
120	0.14	0.36
130	0.13	0.33
140	0.12	0.31
150	0.11	0.29

Production of the blood-mimicking fluid

We used a mixture of 36.5 wt.% glycerol (Glycerol, ReagentPlus® ≥99.0% (GC), St. Louis MO, United States). The temperature was 22°C, which led to a viscosity 2.8 mPa s and approximately 32% HCT. The desired ratio was calculated according to formulas given by Cheng (2008)[1]. The resulted viscosity was validated through a viscometer.

Description of the numerical model of the human blood circulation of the modified hybrid mock circulation

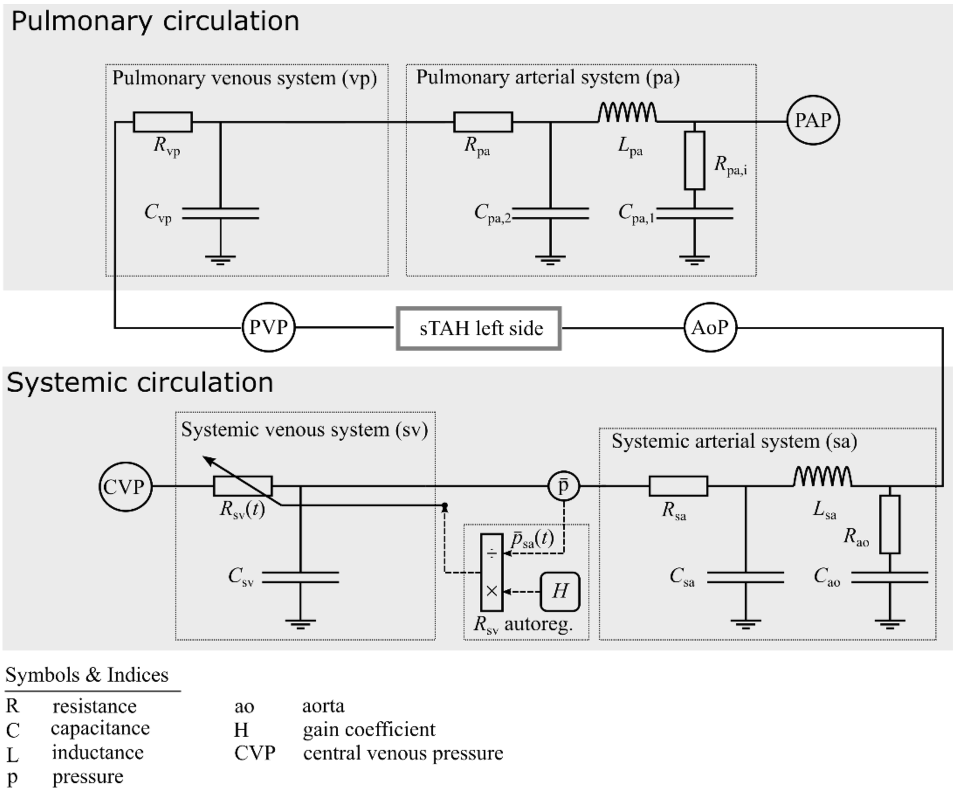

Figure S6. Electric analog of the numerical model of the human blood circulation used for the evaluation of the soft total artificial heart (sTAH) on the modified hybrid mock circulation. The sTAH block is highlighted in grey in the figure to indicate where the interface is implemented.

The PVP and AoP where computed and used for adjusting the pressure of the pressure reservoirs depicted in Figure 3 of the main manuscript. The sTAH left side block represents the left side of the physical prototype we were evaluating. As the physical sTAH right side was not interacting with the numerical model, we had to manually define the corresponding numerical inlet and outlet pressures of the right side, i.e. the central venous pressure(CVP) and the pulmonary arterial pressure(PAP). Therefore, we set and kept constant the CVP of the numerical model (CVPsim, Figure 3 of the main manuscript) and equal to 7 mmHg. The numerical PAP (PAP_{sim}, Figure 3 of the main manuscript) was adjusted by keeping constant the pulmonary vascular resistance at 0.1 mmHg · s/mL. A description and validation of the model, as well as all the values for the additional variables presented in Figure S6 (i.e. the R, L, C elements of the systemic and pulmonary circulation) can be found in the reference 15 of the main manuscript.

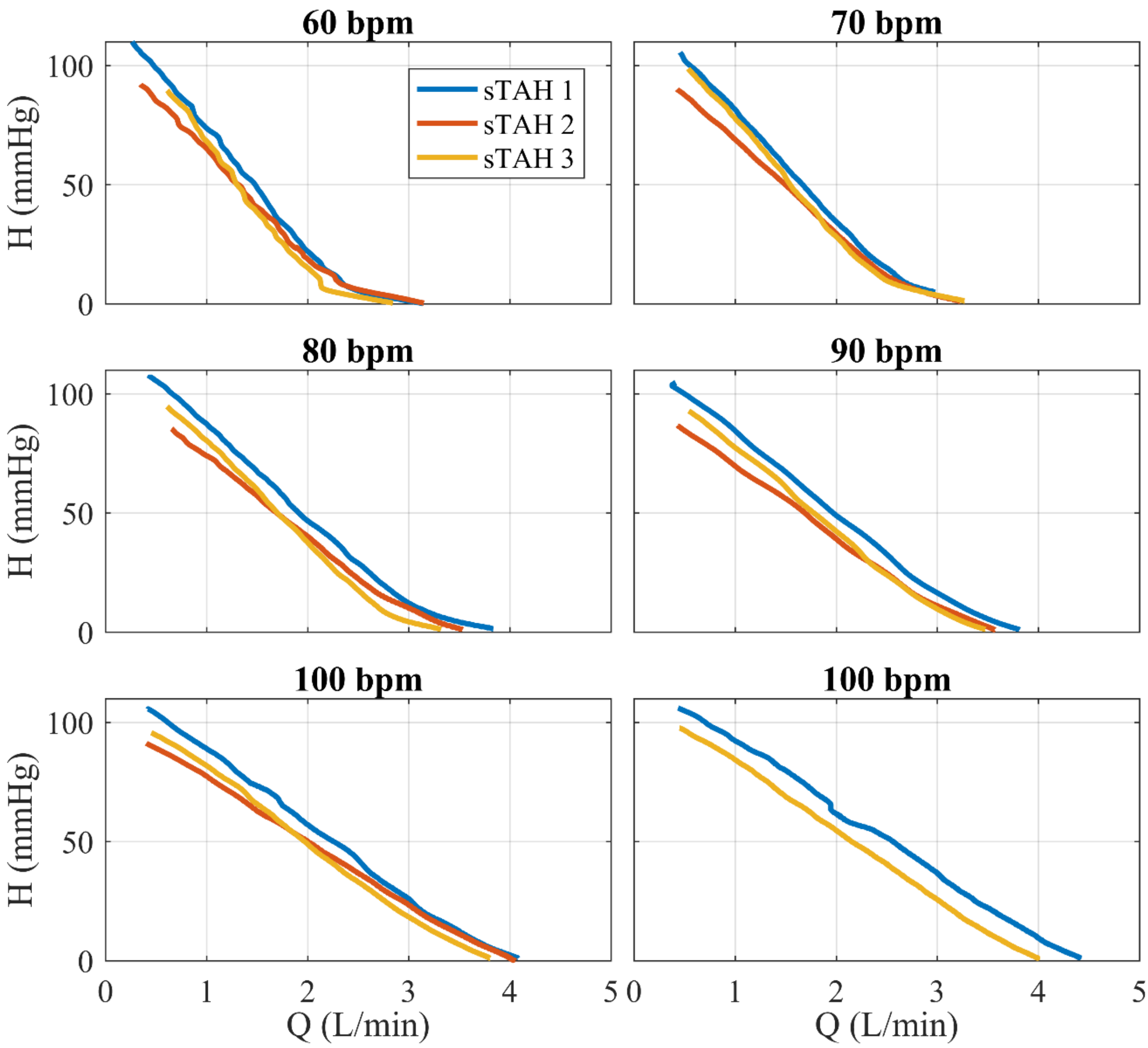

Figure S7.HQ curves with three different prototypes of the soft total artificial heart.

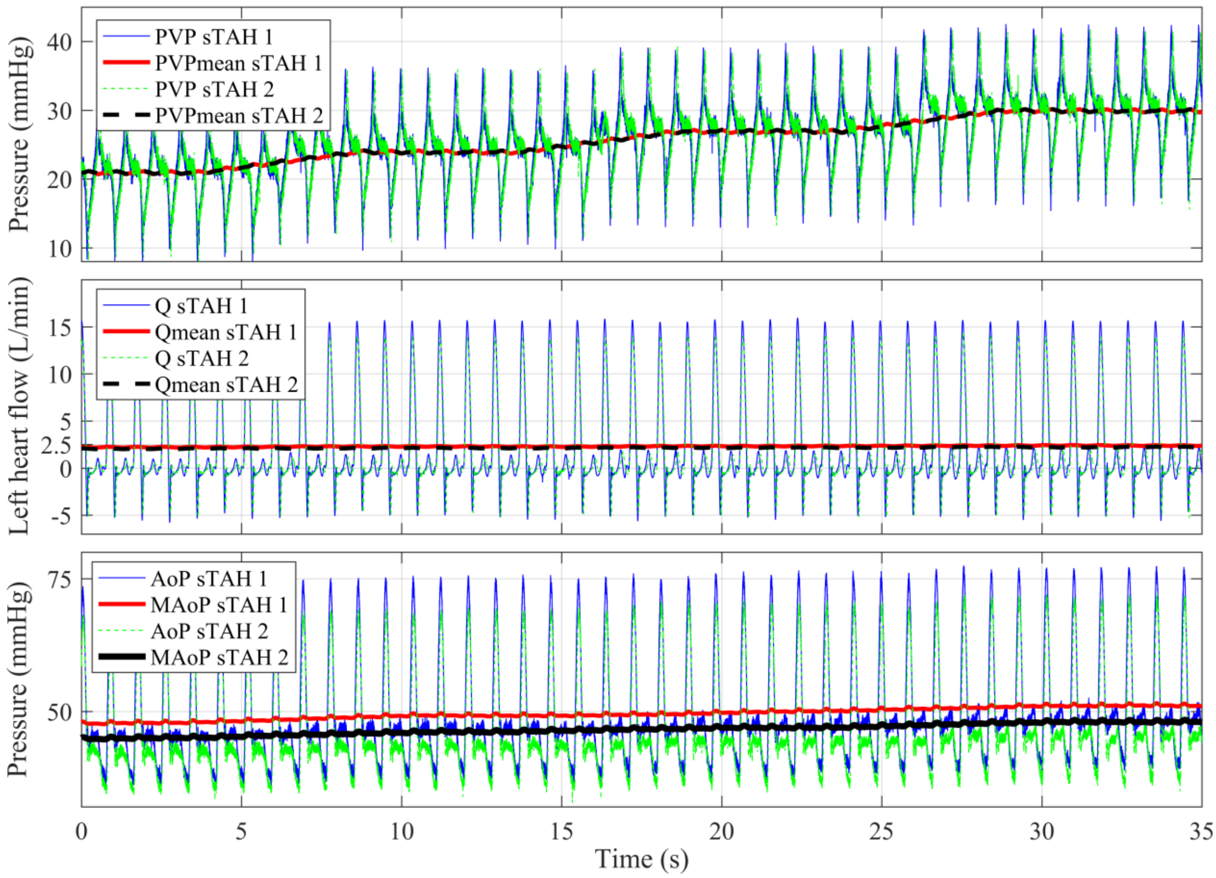

Figure S8: Preload variation experiment with two different prototypes of the sTAH. The signals of the pulmonary mean pressure (PVP), the aortic pressure (AoP) and the left heart flow (Q), as well as their mean values, are depicted.

Full list of experiments

Table S4. Full list of experiments conducted with three soft total artificial hearts until rupture.

Experiment	**Heart prototype**	**Hear rate /bpm**	**Description ***	**Systemic Vascular Resistance (SVR) / mmHg*s/mL**	**PulmonaryVenousPressure / mmHg**	**Pulmonary Vascular Resistance (PVR) / mHg*s/mL**	**Central VenousPressure / mmHg**	**Comment**
1	1	60	LV, stat.	-	-	-	-	ok
2	1	70	LV, stat.	-	-	-	-	ok
3	1	80	LV, stat.	-	-	-	-	ok
4	1	90	LV, stat.	-	-	-	-	ok
5	1	100	LV, stat.	-	-	-	-	ok
6	1	110	LV, stat.	-	-	-	-	ok
7	1	120	LV, stat.	-	-	-	-	ok

8	1	60	LV, AV	0.2 to 2.1, step = 1.11	10	0.1	7	ok
9	1	60	LV, PV	1.11	3 to 30, step= 3	0.1	7	ok
10	1	70	LV, AV	0.2 to 2.1, step = 1.11	10	0.1	7	ok
11	1	70	LV,PV	1.11	3 to 30, step= 3	0.1	7	ok
12	1	80	LV, AV	0.2 to 2.1, step = 1.11	10	0.1	7	rupture
13	2	60	LV, stat.	-	-	-	-	ok
14	2	60	LV, AV	0.2 to 2.1, step = 1.11	10	0.1	7	ok
15	2	60	LV, PV		3 to 30, step= 3	0.1	7	ok
16	2	70	LV, stat.	-	-	-	-	ok
17	2	70	LV, AV	0.2 to 2.1, step = 1.11	10	0.1	7	ok
18	2	70	LV, PV		3 to 30, step= 3	0.1	7	ok
19	2	80	LV, stat.	-	-	-	-	ok
20	2	80	LV, AV	0.2 to 2.1, step = 1.11	10	0.1	7	ok
21	2	80	LV, PV		3 to 30, step= 3	0.1	7	ok
22	2	90	LV, stat.	-	-	-	-	ok
23	2	90	LV, AV	0.2 to 2.1, step = 1.11	10	0.1	7	ok
24	2	90	LV, PV		3 to 30, step= 3	0.1	7	ok
25	2	100	LV, stat.	-	-	-	-	ok
26	2	100	LV, AV	0.2 to 2.1, step = 1.11	10	0.1	7	rupture
27	3	60	LV, stat.	-	-	-	-	ok
28	3	70	LV, stat.	-	-	-	-	ok
29	3	80	LV, stat.	-	-	-	-	ok
30	3	90	LV, stat.	-	-	-	-	ok
31	3	100	LV, stat.	-	-	-	-	ok
32	3	110	LV, stat.	-	-	-	-	ok
33	3	120	LV, stat.	-	-	-	-	ok
34	3	60	RV, stat	-	-	-	-	ok
35	3	70	RV, stat	-	-	-	-	ok
36	3	80	RV, stat	-	-	-	-	rupture

***** LV: Left Ventricle; RV: Right Ventricle; stat.: static; AV: afterload variation, PV: preload variation.

Reference

[1] Cheng N-S (2008) Formula for the Viscosity of a Glycerol−Water Mixture. Ind Eng Chem Res 47:3285-3288. doi:10.1021/ie071349z