Amin Aghababaei, Ali Kashefi and Martin Hexamer*

A drive mechanism for a blood pump integrated in an oxygenator

Abstract: The achievement of a low priming volume of the components in an extracorporeal perfusion system for neonatal and pediatric patients is an open research question. This paper presents a concept of a pump-oxygenator in which an oxygenator and a pulsatile blood pump are combined in one housing. For operation of the pump-oxygenator, a special actuating system for the pump process was designed. It consists of a piston pump which is directly coupled with a voice coil actuator (VCA). A servo positioning system was developed to assure the piston motion according to predefined reference trajectories. First experimental results indicate the feasibility of driving this blood pump with a VCA. In an in-vitro study, the pump produced mean flow rates of 60-900 mL/min with stroke frequencies in the range of 60-240 beats per minute.

Keywords: Blood Pump, Pump-oxygenator, Pediatric

https://doi.org/10.1515/cdbme-2018-0012

1 Introduction

To optimize extracorporeal pediatric perfusion systems a low priming volume of the components is an important prerequisite. Moreover, normothermic machine perfusion systems (NMP) for organ preservation require a dedicated pump and oxygenator system to work optimally. Right now, off-the-shelf blood pumps and oxygenators are used which are mostly oversized in view of the mentioned applications. A possible solution for the reduction of the priming volume is the integration of a blood pump in an oxygenator. The primary attempt dates back to 1951 when Dennis et al. proposed an apparatus combining a pump with an oxygenator [1]. In 2009, an integrated maglev pump-oxygenator (IMPO) was introduced by Zhang T et al. [2]. MiniHLM was reported by the Helmholtz Institute. It is a miniaturized heart-lung machine for new-borns (priming volume = 102 mL). All these systems are pump-oxygenators in which a centrifugal blood pump was incorporated. The ExMeTrA, introduced by Steinseifer et al. [3,4] is a novel pediatric oxygenator with an integrated pulsatile pump. The priming volume is 20 ± 2.2 mL, and the oxygen transfer rate is 32 mL/min at a mean blood flow rate of 500 mL/min [5]. In ExMeTrA the actuating mechanism for the pump is a pressurized tubing system made of silicon, which is periodically inflated and deflated with pressurized air. Based on the generated position displacement in conjunction with valves a directed blood stream can be generated. Although the pressurized-air actuating mechanism is simple, it may cause problems due to an uncontrolled air blood contact and the low actuating dynamics of the membrane.

The research presented in this paper is based on a novel pump-oxygenator in which a much simpler but very effective pulsatile pump mechanism is integrated in an oxygenator. For actuating the pump mechanism, we propose a fluid coupling system by which the pump can be fully actuated in both, pressure and suction mode.

2 Pumping system

2.1 Pump-oxygenator

The blood pump in the pump-oxygenator system is based on the displacement pump concept, which was firstly patented in [6]. As shown in Fig. 1, the pump is composed of two concentric hollow cylinders in such a way that the smaller one is placed inside the bigger one. The space between the inner and the outer cylinder, denoted by (3) in Fig. 1, is packed with hollow fibers made of polypropylene. They constitute the gas exchange membrane. The inner cylinder has two separated parts. The upper part has six circular windows (5) which are all covered by a tubular silicone membrane. This membrane is the pumping membrane, and it separates blood from the driving fluid. The inner cylinder is
filled with the driving fluid, e.g. water or Ringer solution, via the actuating port (4). A complete sequence of the pump operation, which is actuated by the liquid via the actuating port (4), includes a suction mode and a pump/pressure mode. The design of the pump is so that the volume behind a silicon membrane window (5) can maximally displace 1 mL. Therefore, the total volume displacement cannot exceed 6 mL per stroke.

### 2.2 Auxiliary pump mechanism

The actuating mechanism of this pump-oxygenator can be either pneumatically or hydraulically. A pneumatic mechanism can only actuate the pump in the pump/pressure mode, while the pumping membrane cannot be actuated actively in the suction mode. To overcome this limitation, we proposed a hydraulic mechanism in which an auxiliary pump was used to actuate the blood pump. Fig. 2 shows the piston pump which served as the auxiliary pump. The piston pump is connected via a tubing system to the actuating port ((4) in Fig. 1) of the blood pump. The driving fluid generates a tight bidirectional coupling between the two pumps. Therefore, the reciprocating motion of the piston in the cylinder causes a synchronized movement of the pumping membrane in the blood pump. In order to generate a directed blood flow, two check valves (artificial heart valves) are necessary, which convert the reciprocating membrane movement in a unidirectional blood stream. The valves are located at the blood inlet and outlet (near (1) and (2) in Fig. 1).

### 2.3 Flow control

During operation, the stroke volume $\Delta V_p$ of the piston pump is transferred to a volume displacement $\Delta V_B$ in the blood pump, which is the stroke volume for blood pumping. With the frequency of motion $f_m$, mean blood flow rate $\bar{Q}_B$ is

$$\bar{Q}_B = \Delta V_B \cdot f_m.$$  

$\Delta V_B$ is coupled to $\Delta V_p$ by a reduction factor $\delta$, which follows from the compliance of the system ($0.9 < \delta < 0.95$). With displacement $\Delta x$ and surface area $A$ of the piston, blood flow can be expressed as

$$\bar{Q}_B = \Delta V_B \cdot f_m \approx \delta \cdot A \cdot \Delta x \cdot f_m$$  

Hence, the mean flow rate can be controlled in an open-loop mode by the piston position.

### 2.4 Driving mechanism

For driving the piston pump a reciprocating motion was generated by a high-bandwidth voice coil actuator (VCA). Its bandwidth was chosen to fulfil the requirement the pumping frequency range for pediatric patients, i.e. 60-200 beats per minute. As shown in Fig. 2, the VCA was directly coupled to the rod of the piston. To study the feasibility of using a VCA for this application (even in a configuration for adults), a powerful VCA was used (SMAC, CAL75-050-75-2-F5A) with a maximum force of 150 N and 50 mm stroke.
To control the piston motion, a servo positioning system including a cascade control system with a feedforward part was designed and implemented on the rapid control prototyping system dSPACE. The cascade control system consisted of control loops for current, velocity, and position. The current and the velocity loop were controlled by PI controllers respectively, while a P controller was used in the position loop.

### 3 Experimental setup

For evaluating the performance of the drive mechanism of the blood pump, an experimental setup was designed in which the blood pump was connected to a mock circulatory system. The mock system consists of a hydraulic resistance and compliance with a cannula simulating a three-element windkessel model. The mock was filled with water or a water-glycol mixture as a surrogate for blood. The important parameters of the system such as pressure and flow were measured via the dSPACE system. In addition, a current sensor and an optical encoder were used to measure current and position for the VCA’s servo control system.

### 4 Results

Three various motion profiles (reference trajectories) were used to evaluate the performance of the driving mechanism, see Fig. 3. They include a sinusoidal and two trapezoidal profiles with an identical stroke of 3 mm and a motion frequency of 120 beats per minute. The only difference between trapezoidal profile I and II are the timing of the pump and the suction mode (systolic and diastolic duration). The results indicate that the motion with shorter pumping interval (systolic duration) can generate a higher mean flow rate, while the piston stroke was maintained constant.

To evaluate the performance of the pump-oxygenator and its driving mechanism for the desired pumping frequency range, an experiment was carried out with a sinusoidal motion profile and various strokes (e.g. 1, 2, 3 mm). The frequency of motion was varied between 30-240 beats per minute. The results corresponding to the mean flow rate is illustrated in Fig. 4. As can be seen, the proposed drive system can actuate the pump in the desired range, although the measured mean flow rates at frequencies greater than 140
beats per minute did not match the theoretical values (dashed lines in Fig. 4).

Based on these experiments the effective power of the system, especially of the VCA, can be roughly estimated. Fig 5 shows the root mean square (rms)-current of the VCA operated with various stokes, while the supply voltage was 24 V. As can be seen, the current passing through the VCA increases with the stroke. With a stroke of 3 mm, the electrical power is about \(24V \cdot 0.6A = 14.4W\). This value is also a rough estimate of the mechanical power which a VCA must generate to drive the piston pump and the pump-oxygenator. Due to electrical losses the actual mechanical power, generated by the VCA, is of course smaller than 14.4W.

5 Discussion and conclusion

A pump-oxygenator was presented that can be used for the extracorporeal perfusion of pediatric patients or the normothermic machine perfusion of isolated organs. The proposed pump mechanism can fulfill the requirements of these perfusion systems in terms of the mean flow rate. Moreover, the intrinsic pulsatile behaviour of the proposed blood pump allows the perfusion system to profit by the advantages of pulsatile perfusion. To actuate this pump, a fluid coupling system was presented by which the pump sequences can be fully actuated. The overall system can produce mean flow rates in the range of 60-900 mL/min with pumping frequencies in the range of 60-240 beats per minute. Limitations: The low-dynamic behaviour of the used passive check valves may affect the pumping performance at high motion frequencies. Although active valves might be a solution, the potential blood cell damage and the high noise level of these valves are two important aspects that must be investigated precisely. Moreover, increasing the pumping frequency leads to a mismatch between the measured flow rate and the expected value. Undesired vibrations of the pumping membrane at high-frequencies might be a reason. Besides, the non-ideal switching of the check valves can escalate this problem.

Influence of the motion profile: Despite constant motion frequencies and piston strokes, different motion profiles (reference trajectories) of the servo system had an impact on the generated mean flow rates. Those motion profiles with shorter systolic durations, i.e. higher accelerations of the driving fluid, generated higher mean flow rates. Some of the mentioned uncertainties with respect to the actual blood flow rate can be overcome by closed loop control of blood flow rate.

The mechanical design of the piston pump plays an important role in the performance of the pumping system. The friction between piston and cylinder, any misalignment in the coupling between the piston and the VCA, and fluid leakage in the piston pump are main issues that can degrade the pumping efficiency. Naturally, the leakage can be reduced by increasing the number of sealing rings. But, simultaneously the friction is increased and the VCA requires more power.

Ongoing research is focused on improvements of the mechanical design and intelligent control algorithms.

Author Statement

Research funding: This work was supported by the Federal Ministry for Economic Affairs and Energy in Germany (Gefördert durch: Bundesministerium für Wirtschaft und Energie aufgrund eines Beschlusses des Deutschen Bundestages. Förderkennzeichen: 16KN039229). The authors express their sincere gratitude for this contribution.
Conflict of interest: Authors state no conflict of interest.
Informed consent: Informed consent is not applicable. Ethical approval: The conducted research is not related to either human or animal use.

References