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# **THE EFFICIENCY OF AN AFFORDABLE REUSABLE OXYGENATOR FOR WARM KIDNEY MACHINE PERFUSION**

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# The efficiency of an affordable reusable oxygenator for warm kidney machine perfusion

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**Abstract— Objective:** Transplant medicine is a hot topic in current research, especially the preservation part. A lot of research is being done to improve the machine perfusion method, however this is expensive. To reduce costs, the University Medical Center Groningen (UMCG) is working on a budget perfusion system. One of the expensive parts in the current circuits is the oxygenator that provides oxygen to the organ and extracts CO<sub>2</sub>. An affordable version was designed and tested before with water. Goal of this study is to investigate if the budget oxygenator is efficient enough with blood as perfusion medium, to provide a kidney with sufficient oxygen.

**Methods:** During this experiments three oxygenators were tested: MEDOS Hilite 1000, Hemocor HF mini and the UMCG-designed oxygenator. These oxygenators are singly connected to a mock circulation loop flushed with heparinized porcine blood. Flows from 50-500 mL/min with FiO<sub>2</sub>'s of 21, 50 and 100% were tested at gas:blood flow ratios of 1:1, 0.5:1 and 2:1. Every minute the pressure, flow, temperature and pO<sub>2</sub> of the arterial and venous blood were measured. At the highest flows, blood gases were taken and analyzed as well. Due to an adaption after previous research, the UMCG oxygenator has been tested with water flushing through the circuit first to see if it could oxygenate at higher flows as well.

**Results:** The UMCG-designed oxygenator is able to provide gas exchange in water at higher flows. In blood the oxygen delivery is higher than the oxygen demand of a kidney at flows 100-300 mL/min with FiO<sub>2</sub> 100%: 45.0-557.4 mL/min. The inspiration fraction of 21% gives higher oxygen delivery at flows from 300-500 mL/min (excluding ratio 0.5:1 at flow 500 mL/min): 50.4-194.0 mL/min. Comparing the UMCG oxygenator to the MEDOS Hilite 1000, the oxygen delivery is less and more unstable.

**Conclusion & discussion:** It seems that the UMCG-designed oxygenator is not stable enough to provide a porcine kidney with oxygen during perfusion. This might be due to the design, whereas the blood does not flow optimally through the oxygenator. As this is based on single results, further research should be done to draw reliable conclusions and improve the oxygenation capacity of the oxygenator.

**Index Terms—** Budget, kidney, low-cost, oxygenator, perfusion, preservation

## I. INTRODUCTION

ORGAN preservation is an important topic in the world of organ donation and transplantation. In general, static cold storage has been used for a long time to preserve organs over time between removal from the donor and transplantation in the patient. However, machine perfusion has many benefits in comparison to static cold storage. [1] Therefore a shift is being noticed in clinical preservation methods of the organs for transplantation. In The Netherlands kidneys, for example, are standardly preserved with hypothermic machine perfusion instead of the old static cold storage. In the University Medical Center Groningen (UMCG) the surgery department has a transplantation research group that is working on different methods of machine perfusion for transplant organs.

With the current machines, machine perfusion is an expensive method to apply, especially for experimental research. Therefore low-budget solutions are necessary to make it feasible to do more research on this method. An essential part of the perfusion machine is the oxygenator, which is necessary to provide the organs with oxygen. Nowadays clinical oxygenators are used in research, which are designed to provide a total human body with oxygen. Because one organ does not need as much oxygen as a whole body, a less efficient oxygenator can be sufficient as well. It is a logical first step to search for such a less expensive replacing oxygenator to reduce costs for experimental research.

The UMCG has started with designing an affordable reusable oxygenator for experiments with normothermic porcine kidney perfusion. This oxygenator was home-made by the technical service that is part of the UMCG and is reusable, and lower in costs in comparison to a currently used disposable oxygenator. Goal of this study is to see if this oxygenator is suited for providing sufficient gas exchange during kidney perfusions at 37 degrees Celsius.

## II. DEVELOPMENT OF OXYGENATORS IN MACHINE PERFUSION

The first artificial oxygenator for perfusion of a kidney was used in 1882, creating a foundation for many developments coming after. [2] However, it was not until 1953 when the first human intracardiac surgery could be done successfully with a mechanical extracorporeal pump-oxygenator. [2, 3] This oxygenator had a series of parallel and vertically arranged

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wire mesh screens placed in a reservoir. [2] The blood flowed down the screens in this reservoir which created a blood film, making gas exchange possible on the surface of this film. [2-4] The oxygenator was relatively large due to the size of the six to eight used screens of each 60 cm × 10 cm. [2] After some improvements this became the first oxygenator that was commercially available, called the ‘Mayo-Gibbon pump-oxygenator’. [2, 5] After this innovation, the development of oxygenators went fast. Two types can be differentiated: direct-contact oxygenation and oxygenation over a membrane, which gave better oxygenation capacity. [3, 5] The first group contains bubble oxygenators, which bubbled oxygen through the blood; rotating disc oxygenators that used one or multiple rotating discs to film the blood; and screen oxygenators like the Mayo-Gibbon type. [2, 3] The membranes of the second type oxygenator were made of different types of material like silicon or polypropylene, and were used in different configurations: stacked flat sheets or coiled envelopes that were used for disposable oxygenators. [3] These are all gas-exchangers that used an intracapillary perfusion method. [3, 4] Over time the intracapillary oxygenators were replaced by the hollow-fiber membrane oxygenator that uses an extracapillary blood flow, commercially available since the 1980s. [4, 5] It consists of polypropylene microporous hollow-fiber membranes that have a 0.2 μm silicone coating, with blood flowing on the outside and gas flow inside the fibers. [3, 4] This type of oxygenator was and still is popular due to its easy-to-use and significantly more efficient type of gas exchange and its ability to be consecutively used for a longer time (up to 5 months, experimentally tested). [3, 4] Due to the permeability of the separating membrane, gas exchange can take place between the blood and gas.

With all the different oxygenators developed over the years, different design variables seem to influence the performance of an oxygenator, shown in Table I. [3]

TABLE I  
DESIGN VARIABLES INFLUENCING OXYGENATOR PERFORMANCE

|                           | Gas transfer | Prime volume | Pressure drop | Platelet activation |
|---------------------------|--------------|--------------|---------------|---------------------|
| ↓ <i>Fiber diameter</i>   | ↑            | ↓            | ↑             | ↑                   |
| ↑ <i>Packing fraction</i> | ↑            | ↓            | ↑             | ↑                   |
| ↑ <i>Membrane area</i>    | ↑            | ↑            | ↓             | ↓                   |
| ↓ <i>Frontal area</i>     | ↑            | -            | ↑             | ↑                   |
| ↓ <i>Shunting</i>         | ↑            | -            | ↑             | -                   |

↑ = increase; ↓ = decrease; - = no change.

### III. CURRENT EXPERIMENTS

Till now, the oxygenator has only been tested with water in a mock circulation loop. [1] I. Schmidt (2016) studied how different temperatures, flow rates and  $FiO_2$ 's influence the oxygenation capacity of the UMCG oxygenator compared to two other commercially available oxygenators (MEDOS Hilite

1000 and Hemocor HF Minifilter). The study showed that the UMCG oxygenator has a significant lower oxygenation capacity than the currently used oxygenator (Hilite 1000), possibly caused by the much smaller gas exchange area and less permeable membrane. [1] This causes a better performance at low flows, 50 mL/min seemed to be the best flow rate to oxygenate the water with a  $FiO_2$  of 100%. [1] Outcome of the experiments was that the UMCG oxygenator does not provide enough oxygen to water to be able to oxygenate a porcine kidney. [1]

Because water has different characteristics than blood, porcine blood will be used in this following project to check if the oxygen exchange is adequate with blood as perfusion medium. In blood the biggest part of the oxygen is bound to hemoglobin and only a small fraction is dissolved in the aqueous blood plasma. This leads to the expectation that the oxygen delivery of the UMCG oxygenator will be higher with blood than with water.

In the experiment of I. Schmidt (2016) the UMCG oxygenator could only take flows up to 200 mL/min. For this experiment the in- and outlet of the oxygenator are enlarged, decreasing the resistance and making it possible to perfuse with higher flows. To prove this, the UMCG oxygenator will be tested with water first.

### IV. OXYGEN DELIVERY, CONSUMPTION AND EXTRACTION RATIO

To be able to determine the sufficient amount of oxygen that the oxygenator has to deliver to the blood, the tissue oxygen consumption of a porcine kidney must be known ( $VO_{2\text{kidney}}$ ). It is difficult to determine which values in literature are correct for the kidneys used in the Surgery Research Laboratory in the UMCG, because there is a lot of difference in breeds of the pigs described in other studies. The kidneys used in the Surgery Research Lab can be compared to human kidneys, therefore human physiology numbers are used. To determine the oxygen consumption of a porcine kidney, the human oxygen extraction ( $VO_{2\text{human}}$ ) and human renal oxygen extraction ratio are necessary. These normal values are ±250 mL/min and <15%, respectively. [6] Multiplying these two values gives the renal oxygen consumption:  $VO_{2\text{kidney}} = 250 \times \frac{15}{100} = 37.5 \text{ mL O}_2/\text{min}$ .

Oxygen in the blood is transported in two ways: bound by hemoglobin and diluted in the blood plasma. Equation (1) can be used to calculate the total oxygen delivery (DO<sub>2</sub>) of the oxygenator. [6, 7]

DO<sub>2</sub> is the oxygen delivery in mL/min, Hb is the hemoglobin concentration of the porcine blood in g/dL, 1.34 is the amount that hemoglobin can bind in mL O<sub>2</sub>/g, SaO<sub>2</sub> is the arterial saturation (%), PaO<sub>2</sub> is the arterial oxygen tension in mmHg, 0.003 is the solubility coefficient for blood in mL O<sub>2</sub>/100 mL/mmHg, and Q is the flow rate in L/min. [6-8]

$$DO_{2\text{total}} = [(1.34 * Hb * SaO_2) + (0.003 * PaO_2)] * 10 * Q. \quad (1)$$

Another method to calculate the DO<sub>2</sub> difference that is found in literature, is the difference in oxygen tension multiplying by the flow (2). [9, 10] PaO<sub>2</sub> is the arterial oxygen tension in kPa, PvO<sub>2</sub> the venous oxygen tension in kPa and Q is the flow in mL/min. This gives a DO<sub>2</sub> in mL O<sub>2</sub>/min that can be compared to the calculated consumption. [8]

$$DO2_{\Delta} = (PaO_2 - PvO_2) * Q. \quad (2)$$

A porcine kidney study in the UMCG showed that the oxygen saturation after the kidney often is >95%. [11] This means the kidney extracts most of its oxygen demand from the dissolved oxygen. Therefore the second equation will be more useful for this study.

The oxygen demand is met when DO<sub>2</sub> ≥ VO<sub>2</sub>, thus when DO<sub>2Δ</sub> ≥ 37.5 mL O<sub>2</sub>/min for a porcine kidney.

## V. MATERIALS & METHODS

### A. Test oxygenators

Three different oxygenators will be tested in this study. The Hilite 1000 oxygenator (MEDOS Medizintechnik AG, Stolberg, Germany) is used, providing sufficient oxygen for a single porcine kidney. [9] This oxygenator will be used as a control for a Hemocor HF Mini hemofilter (Minntech Corp., Minneapolis, USA) and the UMCG oxygenator. The specifications are shown in Table II.

#### 1) Hilite 1000 (MEDOS Medizintechnik AG, Stolberg, Germany) [12]

This oxygenator is an hollow-fiber gas exchanger with microporous polypropylene fibers. It has a surface of 0.39 m<sup>2</sup> and can reach blood flow rates in the range of 0.15-1 L/min. It is designed for extra-corporeal perfusion in neonatal patients. This oxygenator has an integrated heat exchanger of polyethylene.

#### 2) Hemocor HF Mini (Minntech Corp., Minneapolis, USA) [13]

This hemofilter contains hollow polysulfone membrane fibers, creating a gas exchange area of 0.07 m<sup>2</sup>. It is originally designed for ultrafiltration of neonates to remove small- and medium-sized solutes.

#### 3) UMCG oxygenator (University Medical Center Groningen, Groningen, The Netherlands)

This oxygenator is designed by the UMCG as a reusable budget replacement of the Hilite 1000 oxygenator for experimental research. It consists of a chamber that has small silicone tubing along the chamber, and two in- and outlets. Perfusate can flow from the inlet to the outlet on the top, along the hollow non-porous silicone fibers, whereas oxygen gas flows through these fibers via the inlet and outlet on both sides. This creates a gas exchange area of 0.10 m<sup>2</sup>. [1]

TABLE II  
SPECIFICATIONS OF THE THREE TEST OXYGENATORS

|                   | Hilite 1000                                | HF Mini                    | UMCG oxygenator      |
|-------------------|--|----------------------------|----------------------|
| Priming volume    | 57 mL                                      | 14 mL                      | X                    |
| Gas exchange area | 3900 cm <sup>2</sup>                       | 700 cm <sup>2</sup>        | 1000 cm <sup>2</sup> |
| Fiber material    | Polypropylene                              | Polysulfone                | Silicone             |
| Price             | € 300,-                                    | € 145,-                    | X                    |
| Flow range        | 0.15-1.0 L/min                             | 0-200 mL/min               | To be tested         |
| Manufacturer      | MEDOS Medizintechnik AG, Stolberg, Germany | Minntech, Minneapolis, USA | UMCG, Groningen, NL  |

### B. Experimental setup

To be able to measure the oxygenation capacity of the oxygenators, a mock circulation loop is assembled. A schematic view is shown in Figure 1. This circulation contains a centrifugal pump (Deltastream, MEDOS Medizintechnik AG, Stolberg, Germany), a de-oxygenator (HILITE 1000, M MEDOS Medizintechnik AG, Stolberg, Germany), and one of the test oxygenators (Table II). The oxygenators can be changed in the circuit by their in- and outlet connectors. A de-oxygenator with an integrated heat exchanger is used to control the temperature of the perfusate, keeping it at a temperature of 37 °C. Information about the temperature will be provided by temperature probes (ECOPS temperature probe, Organ Assist B.V., Groningen, NL) after the reservoir and the oxygenator.

De-oxygenation will be done with 100% nitrogen gas at 0.5 L/min. At the venous (inlet) and arterial (outlet) side of the oxygenator real-time oxygen sensors (Presens PST3, Precision Sensing GmbH, Regensburg, Germany) are placed to measure the PaO<sub>2</sub>. The difference between the PaO<sub>2</sub> values provides information about the capacity of the oxygenator. Blood gasses will be taken at the highest flow (500 mL/min), post-oxygenator, for SaO<sub>2</sub>, hemoglobin content and a control of the PaO<sub>2</sub>.

The flow in the system is monitored using an ultrasonic clamp-on probe (ECOPS flow clamp, Organ Assist B.V., Groningen, NL), after the oxygenator. By using pressure transducers, zero-calibrated to the atmosphere (TruWave disposable pressure transducer, Edwards Lifesciences, Irvine, CA), in front of the reservoir, the pressure can be monitored.

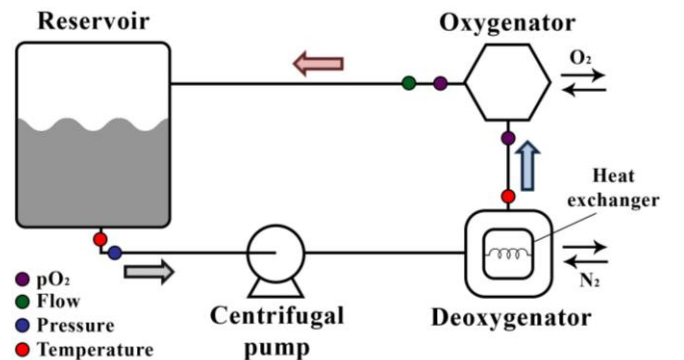


Fig. 1. Schematic view of the mock circulation loop

The oxygenators are provided with different gas mixtures, since a higher oxygen transfer rate can be reached with higher  $\text{FiO}_2$ . According to the AAMI/ISO standards 50% and 100%  $\text{FiO}_2$  are chosen, with ventilation ratios of 0.5:1, 1:1 and 2:1 (gas flow: blood flow). [14] We included as well the atmospheric 21%  $\text{FiO}_2$ . The oxygenators will be tested at flows ranging from 50-500 mL/min.

The perfusion is regulated by a perfusion machine (ECOPS, Organ Assist B.V., Groningen, NL) that can be set up with the desired temperature and flow. Heparinized porcine blood from the slaughterhouse will be used as perfusion medium. According to the international standard (AAMI ISO 7199) water or bovine blood should be used while testing for intended clinical use. [14] However, this study is not even close to the stadium of clinical use and because the other perfusion experiments in the surgical research lab of the UMCG use porcine kidneys and blood, we will use porcine blood as well to be able to compare our findings.

### C. Data collection and analysis

Every set of parameters will be tested for 5 minutes, taking measurements of the temperature, flow,  $\text{pO}_2$  at the inlet and outlet every minute. During the tests blood gases of the arterial blood will be taken for every  $\text{FiO}_2$  with each ventilation ratio at the highest flow, from which the Hb,  $\text{SaO}_2$ , and  $\text{PaO}_2$  can be measured. Blood gases are taken at this point in the experiment, because saturation will be worse at higher flows. Calculating  $\text{DO}_2$  with the lowest saturation will give minimal values that can be compared to the  $\text{VO}_2$ , preventing overestimation of the capacity. If this minimal value is above the  $\text{VO}_2$ , the exact value will be higher as well. This is not the case when higher saturations (measured at lower flows) will be used for the calculations, as the real  $\text{DO}_2$  at high flows might be lower.

Further analysis is done with mean values of measurements and calculations. Oxygen capacity is the difference in  $\text{PaO}_2$  between arterial and venous blood. The oxygen delivery can be calculated by equation (2) with the measured parameters. By comparing the variables to kidney consumption, conclusions can be drawn about the efficiency of the oxygenators.

## VI. RESULTS

At the start of the tests with the Hemocor HF Mini hemofilter, the filter appeared to be leaking. The HF Mini is therefore taken out of the experiment.

After doing the experiments it seemed that some of the blood gases could not be analyzed. Therefore the  $\text{DO}_2$  at a ratio of 1:1 could not be calculated for the UMCG-oxygenator with a  $\text{FiO}_2$  of 50%. The  $\text{DO}_2$ 's of the MEDOS Hilite 1000 with a ratio of 2:1 at  $\text{FiO}_2$  21%, ratios 1:1 and 0.5:1 at  $\text{FiO}_2$  50% and all the ratios at  $\text{FiO}_2$  100% are missing for the same reason. Due to a lack of time the experiments could not be redone.

### A. UMCG-oxygenator with water

The oxygenation capacity of the UMCG-oxygenator with water as perfusate for different  $\text{FiO}_2$ 's, flows and ratios is shown in Figure 2-4. A  $\text{FiO}_2$  of 21% gives much lower oxygenation than the other two inspiration fractions. At a  $\text{FiO}_2$  of 50% and 100% the oxygenation capacity is best at flows 50 and 100 mL/min. For  $\text{FiO}_2$  50% a ratio of 2:1 (gas: blood flow) is the most efficient, for 100%  $\text{FiO}_2$  a ratio of 0.5:1 or 2:1.

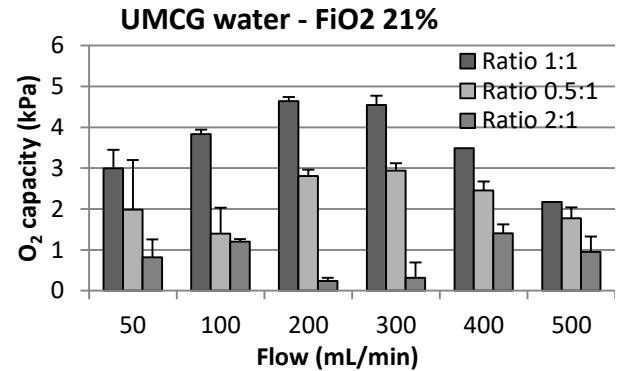


Fig. 2. Oxygenation capacity of the UMCG-oxygenator with water at a  $\text{FiO}_2$  of 21%

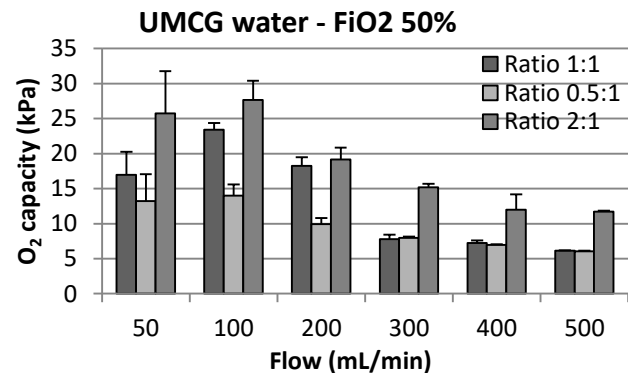


Fig. 3. Oxygenation capacity of the UMCG-oxygenator with water at a  $\text{FiO}_2$  of 50%

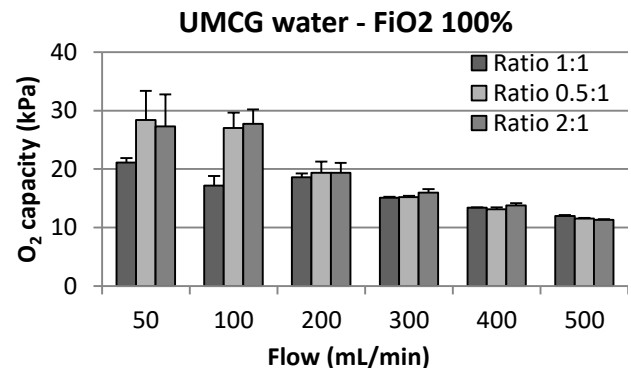


Fig. 4. Oxygenation capacity of the UMCG-oxygenator with water at a  $\text{FiO}_2$  of 100%

### B. UMCG-oxygenator with porcine blood

The difference in partial oxygen pressure with the UMCG-oxygenator tested with porcine blood is shown in Figure 5-7. Table III shows the measured hemoglobin and saturation values. With a higher  $\text{FiO}_2$  there is more oxygen delivery. It is

notable that at an inspiration fraction of 100% the  $\Delta pO_2$  optimum is around 100 mL/min. The  $FiO_2$  of 21% and 50% gives irregular oxygen delivery values.

The  $DO_{2\Delta}$  values can be calculated with equation (2). At the inspiration fractions of 21% and 50% the oxygen delivery increases with an increasing flow. At flows 300-500 mL/min the  $DO_{2\Delta}$  is in the range 50.4-194.0 mL/min. Only ratio 0.5:1 at flow 500 mL/min had a  $DO_{2\Delta}$  outside this range, an oxygen delivery of 31.0 mL/min. Flows 50- 200 mL/min had  $DO_{2\Delta}$  values of 6.0-33.2 mL/min, excluding ratio 2:1 at a 200 mL/min flow ( $DO_{2\Delta}=52.4$  mL/min). Like the  $\Delta pO_2$ , the inspiration fraction of 50% had very irregular  $DO_{2\Delta}$  values. All ratios at flow 50 mL/min and ratio 0.5:1 at flow 300 mL/min had  $DO_{2\Delta}$  values between 6.30-20.8 mL/min. The other variables gave  $DO_{2\Delta}$ 's in the range of 41.0-243.2 mL/min. The highest inspiration fraction had  $DO_{2\Delta}$  values of 45-557.4 mL/min at flows 100-300 and 500 mL/min. The  $DO_{2\Delta}$ 's of the other flows are in the range of 4.8-24 mL/min.

During the tests it looked like the blood flow did not reach the whole oxygenator, but only flowed lengthwise on the surface. The peak at  $FiO_2$  50%, ratio 0.5:1 and flow 100 mL/min is caused by turning the oxygenator upside down, which caused a more effective flow through the oxygenator at that single moment.

When the tests were done for a second time, the oxygenator appeared to be leaking. Blood flowed along the tube attachments into the gas area, making it impossible to redo the tests.

TABLE III

HEMOGLOBIN AND SATURATION VALUES FROM THE UMCG OXYGENATOR

|                  | $FiO_2$ (%) | Ratio (gas flow: blood flow) |       |     |
|------------------|-------------|------------------------------|-------|-----|
|                  |             | 1:1                          | 0.5:1 | 2:1 |
| Hb               | 21          | 7.9                          | 7.9   | 7.9 |
|                  | 50          | -                            | 8.0   | 8.0 |
|                  | 100         | 8.1                          | 8.1   | 8.1 |
| SaO <sub>2</sub> | 21          | 34                           | 31    | 22  |
|                  | 50          | -                            | 56    | 68  |
|                  | 100         | 77                           | 80    | 81  |

Values obtained from blood gases taken at flows of 500 mL/min

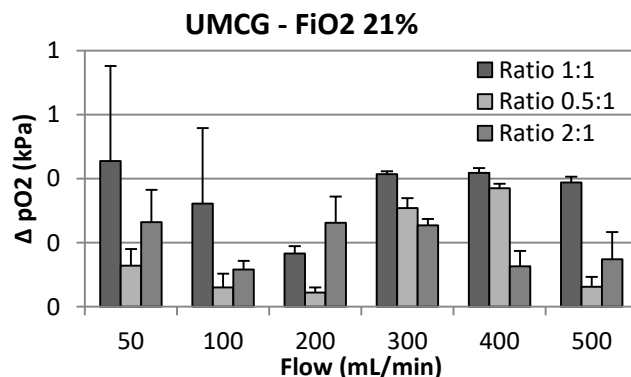


Fig. 5. Difference of partial oxygen pressure in arterial and venous blood with the UMCG oxygenator with porcine blood at a  $FiO_2$  of 21%

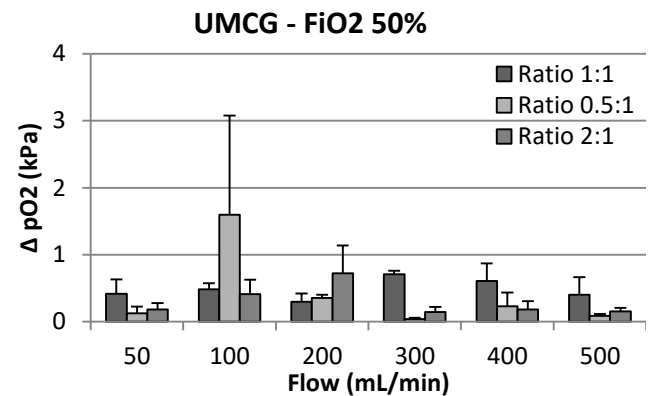


Fig. 6. Difference of partial oxygen pressure in arterial and venous blood with the UMCG oxygenator with porcine blood at a  $FiO_2$  of 50%

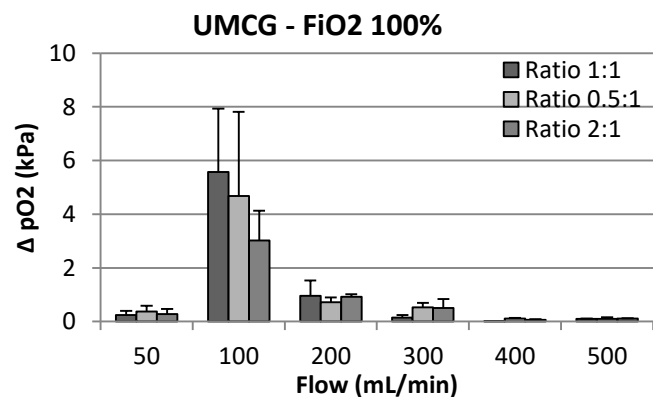


Fig. 7. Difference of partial oxygen pressure in arterial and venous blood with the UMCG oxygenator with porcine blood at a  $FiO_2$  of 100%

### C. MEDOS Hilite 1000 with porcine blood

The difference in partial oxygen pressure with the MEDOS Hilite 1000 with porcine blood is shown in Figure 8-10. The Hb and SaO<sub>2</sub> results of the blood gases, as far as analyzed, are shown in Table IV.

The  $DO_{2\Delta}$ 's can be calculated with equation (2). An increase in blood flow shows an increase in  $DO_{2\Delta}$ . It can be noticed that there is a big difference in oxygen delivery between inspiration fraction 21% and the other two fractions. Fraction 21% gives an delivery in oxygen in the range 399.0-7,200.0 mL/min.  $FiO_2$  50% has  $DO_{2\Delta}$ 's between 1,941.1-31,115.6 mL/min. The highest inspiration fraction of 100% gives  $DO$ 's of 3,036.5-31,751.6 mL/min.

During the tests with the Hilite 1000, the blood clotted twice after which the blood had to be replaced.

TABLE IV  
HEMOGLOBIN AND SATURATION VALUES FROM THE HILITE 1000  
OXYGENATOR

|                  | FiO <sub>2</sub> (%) | Ratio (gas flow: blood flow) |       |     |
|------------------|----------------------|------------------------------|-------|-----|
|                  |                      | 1:1                          | 0.5:1 | 2:1 |
| Hb               | 21                   | 9.3                          | 9.3   | -   |
|                  | 50                   | -                            | -     | 9.6 |
|                  | 100                  | -                            | -     | -   |
| SaO <sub>2</sub> | 21                   | 76                           | 96    | -   |
|                  | 50                   | -                            | -     | 85  |
|                  | 100                  | -                            | -     | -   |

Values obtained from blood gases taken at flows of 500 mL/min

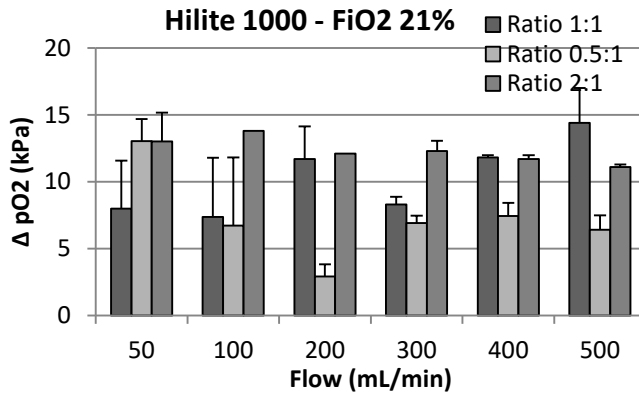


Fig. 8. Difference of partial oxygen pressure in arterial and venous blood with the HILITE1000 oxygenator with porcine blood at a FiO<sub>2</sub> of 21%

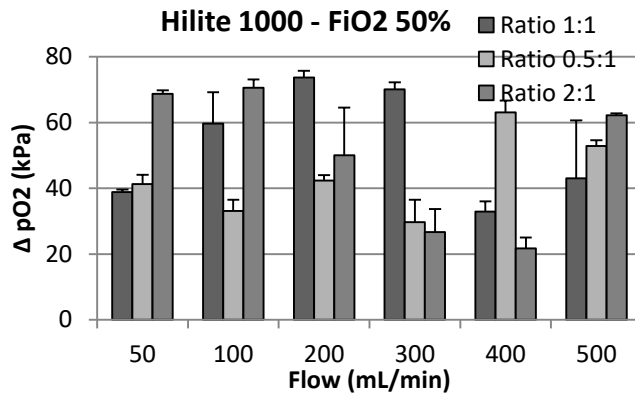


Fig. 9. Difference of partial oxygen pressure in arterial and venous blood with the Hilite 1000 oxygenator with porcine blood at a FiO<sub>2</sub> of 50%

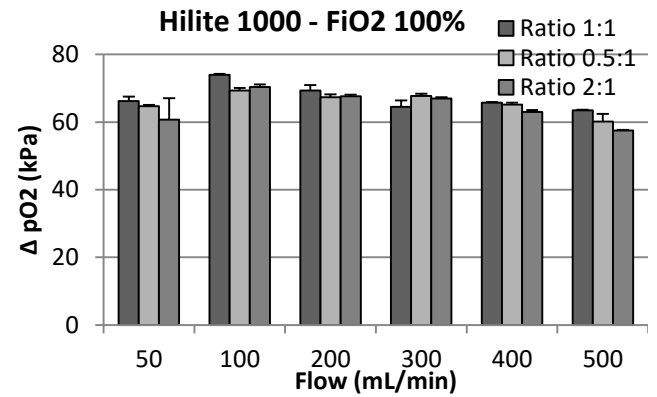


Fig. 10. Difference of partial oxygen pressure in arterial and venous blood with the Hilite 1000 oxygenator with porcine blood at a FiO<sub>2</sub> of 100%

## VII. DISCUSSION & CONCLUSION

This project was done to investigate if the UMCG-designed oxygenator could provide sufficient oxygen for a porcine kidney in experimental research with normothermic perfusion. Looking at the data of the test with water, it seems that the oxygenator can effectively provide gas exchange between the gas and the blood, adding oxygen to the water. Due to the increased in- and outlet in comparison to the tests done before, gas exchange at higher flows 300-500 mL/min is possible. Therefore the experiment with porcine blood could go up to 500 mL/min for the UMCG oxygenator as well.

Taking a look into the results of the blood-experiment, it seems that the UMCG oxygenator cannot provide enough oxygen for a porcine kidney at all tested situations. The lowest flow, 50 mL/min seems unsuited for kidney perfusion due to the low oxygen delivery. It is hard to say something about the 50% inspiration fraction, due to the irregular results from this tests. It should be repeated to be able to draw a conclusion. The highest inspiration fraction, 100%, gives the best result. Flows ranging from 100 to 300 mL/min seem suitable for warm kidney perfusion, as the  $DO_{2\Delta}$  of all fractions is higher than 37.5 mL/min: 45.0-557.4 mL/min. Even the inspiration fraction of 21% gives  $DO_{2\Delta}$ 's higher than the  $VO_{2\text{kidney}}$  at flows from 300-500 mL/min: 50.4-194.0 mL/min, ratio 0.5:1 at flow 500 mL/min excluded. However, these are all preliminary results and therefore no real conclusions could be drawn.

The MEDOS Hilite 1000 has a quite stable increasing oxygen delivery when inspiration fraction and/or flow increases. As expected, the preliminary results show that this oxygenator is suitable for kidney perfusion with all tested variables. Based on these results it is recommended to keep using the MEDOS Hilite 1000 in normothermic kidney perfusion, due to its stable oxygen delivery compared to the UMCG-designed oxygenator. Because the flow might fluctuate during perfusion, it is important that the oxygenator is able to deliver sufficient oxygen at all flows.

In this study it was decided to use equation (2) for the calculation of oxygen delivery, because this equation would describe the most significant part of the oxygen content. However, the hemoglobin content described in equation (1)

might be important as well. Even though studies showed that there is not a big difference in blood saturation, it might be a small important difference. To investigate this, blood gasses should be taken at the venous side too in further research, so the difference in saturation can be taken into account. When this will be done, an organ should be placed into the circuitry as well to de-oxygenate the hemoglobin.

It is possible that the blood did not effectively flow through the whole oxygenator, due to the design of the UMCG oxygenator. To prevent this, the outlet of the oxygenator should be placed on the opposite side of the cylinder, causing the blood to cross the oxygenator in both x- and y-direction. This might improve the oxygenation capacity of the oxygenator. Unfortunately it was not possible to test this in the project due to the production time of a new oxygenator. It can be the next step in research for a low-budget oxygenator.

Due to the limited data of the MEDOS Hilite 1000 it was not possible to draw conclusions about this oxygenator or use it as comparison for the UMCG oxygenator. The results of the blood gases have been retrieved a week after the experiments were done. At that moment it appeared that some blood gases could not be analyzed. When further research will be done, the results of the blood gases should be checked as soon as possible so adaptations can be made when the blood gases are not good.

The results of this project are based on single experiments and are therefore preliminary. To improve the reliability of the data, experiments should be repeated multiple times in further research.

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