INTRODUCTION

Extracorporeal circulation (ECC) is an integral part of cardiac surgery during which the blood gets into contact with artificial surfaces activating its complement and thrombogenic system.1 Centrifugal or roller pumps are commonly used to achieve the necessary continuous motion of the fluid medium. These pumps expose the blood to suction, pressure, and shear forces2 which are likely to further mechanically strain and damage the corpuscular components.3,9 The extracorporeal circulation might, therefore, potentially cause hemolysis10-12 motivating further research on possible targets to reduce these effects.

Abstract

Extracorporeal circulation (ECC) is an integral part of cardiac surgery. Yet, the contact with artificial surfaces, mechanical stress, shear, and suction forces within the ECC pose a pronounced risk for damaging the corpuscular components of the blood. These suction forces may be reduced by a repositioning of the roller pumps employed below the reservoir. Furthermore, the repeated compression of the involved silicone tubing is likely to cause degradation. We present our observations regarding changes in the ECC performance following this degradation process. In vitro experiments were performed in a standard as well as a simplified ECC setup and included measurements of pressure, effective flow, and tubing restoring force over a time frame of 12 hours with two different pump positions utilizing transit time flow measurement. Suction forces within the tubing could be significantly reduced by shifting the pump position below the reservoir. Regardless of the setup, the tubing showed significant loss of restoring force as well as effective flow over time. A shift of the pump position within the ECC setup can be recommended to prevent blood damaging negative pressures. Further research is necessary to evaluate the exact cause of the reduction of restoring force overtime as well as its risks for the patients. Finally, our results underline the importance of transit time flow measurements to collect reliable flow data.

KEYWORDS

degradation, extracorporeal circulation, tubing
Heart-lung machines (HLM) are predominantly equipped with DeBakey pumps, a derivative of Beck's mill, which had originally been developed for blood transfusions.

These pumps are commonly constructed with two diametrically installed rolls. These rolls compress the tubing tightly occluding the blood filled inner compartment. This occlusion continuously moves forward following the motion of the rolls, thereby transporting the fluid inside the tubing segment in the direction of pump rotation. It is often assumed that the flow of these pumps is generated exclusively by the aforementioned occlusion provided by the roller pump. However, this only discharges the compressed tubing segment and prevents the back-flow of the fluid. The refilling is facilitated by the restoring force driven re-expansion of the tubing and potentially passively through the fluid pressure before the pump entrance (Figure 1A). If these driving forces of the tubing refilling do not suffice to ensure a complete recovery of the compressed segment (Figure 1C), the effective flow of the pump will not reach the one calculated from the tubing diameter and pump rotation speed.

With the introduction of a recently acquired HLM in our clinic, we were able to systematically vary the pump's position within the setup. Positioning the pumps above the reservoir can result in reservoir fluid levels ranging only slightly above or even below the entrance of the roller pump (Figure 2A). This in turn would result in very low or even negative pressures within the tubing before the roller pump. Therefore, it can be refilled exclusively through the restoring force further reducing these low or negative pressures.

In contrast to this, a repositioning of the pumps below the reservoir (Figure 2B) will lead to a reliable fluid column standing above the pump entrance. The higher pressures resulting from the gravitational force of this fluid column will support the refilling process and prevent low or negative pressures, which can be harmful for the blood components. Therefore, tests were performed to evaluate possible advantages of shifting the pumps position from above to below the reservoir.

It should be noted that regardless of the reservoir position, application of vacuum forces often routinely implemented in order to enhance venous drainage to the reservoir will even result in a further reduced pressure at the entrance of the roller pump, thereby aggravating the aforementioned consequences.

By performing experiments over prolonged time periods, we furthermore sought to examine if some kind of degradation effect could be detected caused by the constant deformation of the tubing. The initial research hypotheses were:

1. Repositioning of the roller pump below the level of the reservoir will attenuate suction forces (i.e. negative pressures) affecting the fluid in the tubing in front of the pump.
2. Prolonged use of tubing in the roller pump leads to a wear out manifesting itself in a reduction of tubing restoring force leading to a reduced effective flow.

2 | MATERIALS AND METHODS

The performed experiments can be divided into two segments:

2.1 Comparison of different pump positions and tubing ages in a standard ECC setup

All measurements were performed at one ECC of the type C5 (LivaNova, London, United Kingdom). The roller pump was positioned either 36 cm above (in the following referenced as ABOVE) or 7 cm below (BELOW) the reservoir outlet to
SCHRÖTER ET AL.

compare both positions (Figure 2, Table 1). Height measurements to the floor are given in Table 1.

The occlusion was adjusted according to method 1 in the C5 manual. For that the occlusion was adjusted to maximal before clamping the tubing on one side. The roller pump was then manually moved until the tubing segment between the occlusion and the clamp was considerably compressed. The occlusion was then reduced step by step until refilling of the compressed segment started, and then, increased again by two steps. Measurements were performed using our standard setup consisting of an FX25 oxygenator (Terumo, Shibuya, Japan) and a tubing set by Livanova (LivaNova). The tubing segment within the roller pump was made from silicone with a diameter of ½ inch (12.7 mm) and a wall thickness of 3/32 inch (2.4 mm). ECC fine calibration was set to 0%. The external flow-measurement was performed via an ECLS-console ECP (LivaNova), including a transit time flow sensor (Transonic Europe, Elsloo, The Netherlands), with a precision of ±10%, respectively, ±0.1 L/min. These values were compared with the internal calculated flow values to determine the effective flow. 250 mL Osmofundin (B. Braun, Melsungen, Germany) was mixed with Jonosteril (Fresenius Kabi, Bad Homburg, Germany) to achieve the desired priming.

Pressure was measured and documented at multiple points: P1: at the entrance of the roller pump, P2: outlet of the roller pump, P3: behind the oxygenator. Of these, only P1 is reported in this manuscript, since the prevention of suction forces at this point was one main goal of this work. All values were corrected by the pressure gradients caused by the height differences between measurement point and pressure transducer.

To produce a comprehensive overview of the effects caused by pump repositioning, 6-7 measurements were performed at each combination of both tubing ages, both pump position, reservoir levels of 500, 1000, and 2000 mL as well as flows of 3, 4.5, and 6 L/min resulting in a total of 108 measurements for the ABOVE and 113 for the BELOW configuration. These measurements were performed at two separate days for each pump configuration. Pressure downstream of the oxygenator (P3) was adjusted to values of about 250 mm Hg (3 L/min), 300 mm Hg (4.5 L/min), and 350 mm Hg (6 L/min) with a maximum deviation of ±5 mm Hg using a clamp. During this set of experiments, no temperature regulation of the fluid was used. The temperature was documented and varied between 24.3 and 27.6°C for all experiments combined (ABOVE day 1: 25.3-26.1°C, day 2: 25.1-27.6°C, BELOW day 1: 24.3-25.8°C, day 2: 25.6-26.4°C).

Measurements were performed immediately at the start of the experiments. Afterward, pumping was continued for 4-5 hours at 4.5 L/min before repeating the measurements to examine the effect of prolonged pump use on the tubing performance.

### 2.2 Isolated experiments regarding tubing degeneration through prolonged use in roller pumps

To further validate the second hypothesis under controlled conditions a second series of experiments was performed using a simplified build-up mimicking the HLM circulation filled with physiological saline solution. The used setup consisted of a reservoir with oxygenator, a separate S3 roller pump and a flow sensor Stöckert UFM (both Stöckert Instrumente GmbH, Munich, Germany, now LivaNova) which were provided as rental instruments by Elmeditec GmbH (Haren (Ems), Germany). 0.9% NaCl solution (Fresenius, Bad Homburg, Germany) was used as fluid...
medium. To avoid temperature fluctuations, the fluid in the system was kept at 37°C using a Deltastream HC (Medos now Xenios, Heilbronn, Germany). Occlusion was adjusted as described above increasing it by three steps after the refilling of the tubing segment could be observed. The 50 cm long tubing within the roller pump segment was fitted with adapters allowing for easy removal during the restoring force measurements. Height differences between the different components of the setup were kept constant with the values measured to the floor given in Table 2.

To collect reproducible data of restoring forces, the water filled tubing was sealed at both ends and connected to a syringe. By pulling the syringe using a luggage scale, 20 mL of the fluid (corresponding to 28.38% of the fluid content of the tubing with connectors) was removed thereby compressing the sealed tubing (Figure 3). Due to Newton’s third law, the force necessary for pulling the syringe is equal to the tubing restoring force counteracting this compression. To increase reproducibility, all parts of this experimental setup were fixed on a wooden board which provided fixed supports for the scale ensuring a constant fluid extraction over all measurements.

The tubing being tested and constantly being compressed over up to 12 hours in this experimental series was made of silicone, with a diameter of ½ inch (12.7 mm) and a wall thickness of 3/32 inch (2.4 mm). It was provided from different suppliers: Eurosets (Medola, Italy), Medos, Sorin, LivaNova, Raumedic (Helmbrechts, Germany). Raumedic furthermore provided silicone tubing with increased wall thickness (1/8 inch = 3.2 mm) either with (Raumedic 1/8) or without (Raumedic 1/8 -LT) a Lowtack surface which we included in the comparison. Even though supplied by different companies, all tubing was originally produced by Raumedic.

The Shore hardness of the tubing was approximately 60 (Raumedic: 58, LivaNova: 58, Eurosets: 62, Medos: 63). Measurements were performed at five different time points (0, 2, 4, 8, 12 hours) for each pump configuration and tubing. As all used tubings had the same diameter, the number of compressions per hour at each flow rate was the same for each examined tubing. At each time point, 15 repeated measurements of the effective flow were documented by stopping the pump, readjusting it to the target flow and detecting fluid flow using the transit time flow sensor. After these measurements, the tubing segment was separated at the preinstalled adapters to perform 20 measurements of the restoring force. This resulted in 75 effective flow and 100 restoring force measurements for each tubing at each pump configuration. The tubing segment was then reinstalled in the setup to continue the experiment. The pressure value immediately before the roller pump (P1) was too low to be monitored by the pressure transducers at hand. Yet, the evaluation of a potential correlation between restoring force and effective flow over time was the main focus of this experimental series.

### Table 2

| Component                  | Distance to floor [cm] |
|---------------------------|------------------------|
| Reservoir outlet          | 56                     |
| Inlet of roller pump      | 92                     |
| Measurement point P1      | 90                     |
| Pressure transducer       | 119.5                  |

**Figure 3**: Illustration of the experimental setup for restoring force measurements. The force $F_{\text{pull}}$ necessary for pulling the syringe is equal to the restoring force $F_{\text{restore}}$ of the sealed tubing resisting its compression.

### 2.3 Statistical analysis

Statistical analysis was performed using R version 3.4.1 (R Foundation for Statistical Computing, Vienna, Austria). The data of the comparisons in the standard setup were not normally distributed (tested with Shapiro-Wilk test), and therefore, were compared using Mann-Whitney U tests. To account for multiple testing during comparisons of different parameter combinations, the $P$ values were corrected using the Holm-Bonferroni method.

The data in the reduced complexity setup were similarly found to be not completely normally distributed. To examine the significance of trends over time, we therefore used the nonparametric correlation for paired samples (Kendall’s tau).

### 2.4 Graphical representation

Results are presented as boxplots which are commonly defined as follows: The boxes mark the range of the second and third quartile, the whiskers extend from the borders of the box to the most extreme values while being limited to 1.5 times the interquartile range. Values outside the whiskers range are marked with circles as outliers. Medians are indicated by bold lines in the boxes, means by squares.

### 2.5 Confocal microscopy

Slices of tubing either unused or after 12 hours compression in the roller pump were examined for potential traces.
of material tearing using a confocal microscope (IX81, Olympus, Tokyo, Japan). An approximately 0.5 mm thick slice of tubing was cut out from the middle of the tubing segments, put on an object slide and examined using transmission light under 100x magnification.

3 | RESULTS

The performed experiments fall into two segments:

3.1 | Comparison of different pump positions and tubing ages in a standard ECC setup

The flow data collected in the standard ECC setup did not differ between different reservoir levels. Furthermore the differences between the measured pressure values disappeared when these were corrected by the pressure gradients caused by the different fluid levels. Therefore, these data were pooled after this necessary correction resulting in the data shown in Figure 4A,B. The pressure at point P1 was significantly higher after repositioning the roller pump below the level of the reservoir outlet (Figure 4A, red boxes, Tables 3 and 4) regardless of tubing age. Pressure values remained positive at flows of 3-4.5 L/min and were only slightly negative at 6 L/min. In contrast to that, the ABOVE pump position (blue) led to pronounced negative pressure values (dependent on flow) which increased slightly but significantly after prolonged use.

We further compared the effective flow, represented by the quotient between the flow set on the ECC and the one measured at the tubing using a transit time flow sensor. The effective flow significantly dropped in both pump configurations following prolonged use of tubing with the effect being

| TABLE 3 | Mean and standard deviation of pressure values measured before the roller pump and effective flow values measured with the roller pump positioned ABOVE or BELOW the reservoir at different flows using tubing already in use for a short (<1 hour) or longer (>4 hours) period of time |

| | 3 L/min | 4.5 L/min | 6 L/min |
|---|---|---|---|
| P1 [mm Hg] |  |  |  |
| <1 hour ABOVE | -26.78 ± 0.89 | -33.16 ± 0.97 | -41.61 ± 0.44 |
| <1 hour BELOW | 7.22 ± 3.72 | 2.78 ± 3.24 | -2.68 ± 2.91 |
| >4 hours ABOVE | -24.00 ± 1.11 | -30.28 ± 1.09 | -38.33 ± 1.08 |
| >4 hours BELOW | 7.37 ± 1.45 | 3.42 ± 1.61 | -2.10 ± 2.11 |
| Effective flow [%] |  |  |  |
| <1 hour ABOVE | 96.78 ± 0.46 | 100.21 ± 0.56 | 99.03 ± 0.42 |
| <1 hour BELOW | 96.41 ± 1.03 | 97.61 ± 0.99 | 98.88 ± 1.09 |
| >4 hours ABOVE | 94.48 ± 0.99 | 98.01 ± 0.56 | 96.04 ± 0.63 |
| >4 hours BELOW | 95.28 ± 1.19 | 96.59 ± 0.89 | 98.00 ± 1.25 |

Note: Absolute flow values are given in Supporting Information S2.
## Table 4
Significances of comparisons of pressure values P1 and effective flows between different tubing ages and pump positions

|                           | 3 L/min | 4.5 L/min | 6 L/min |
|---------------------------|---------|-----------|---------|
| P1 [mm Hg]                |         |           |         |
| ABOVE <1 vs. >4 hours     | <0.001  | <0.001    | <0.001  |
| BELOW <1 vs. >4 hours     | 1       | 0.691     | 0.180   |
| <1 hour ABOVE vs. BELOW   | <0.001  | <0.001    | <0.001  |
| >4 hours ABOVE vs. BELOW  | <0.001  | <0.001    | <0.001  |
| Effective flow [%]        |         |           |         |
| ABOVE <1 vs. >4 hours     | <0.001  | <0.001    | <0.001  |
| BELOW <1 vs. >4 hours     | 0.028   | 0.012     | 0.063   |
| <1 hour ABOVE vs. BELOW   | 0.589   | <0.001    | 0.988   |
| >4 hours ABOVE vs. BELOW  | 0.095   | <0.001    | <0.001  |

*Note:* Comparisons were performed using pairwise Mann-Whitney U tests. P values were corrected for multiple testing according to the Holm-Bonferroni-method.

### Figure 5
Restoring force [in % of mean value at 0 hour] over time in tubing from different providers in the ABOVE (blue) and BELOW (red) configuration. All tubing was originally produced by Raumedic. Medians are indicated by bold lines, means by squares within the boxes. 3/32: material thickness 3/32”, 1/8: material thickness 1/8”, -LT: no low tack surface coating. Significance of trend tested by correlation for paired samples (Kendall’s tau) is indicated by black asterisks (*P < .05: *, **P < .01: **, ***P < .001: ***")
more pronounced in the ABOVE configuration (Figure 4B, blue boxes, grey vs. white filling, Table 1).

### 3.2 Comparison of different pump positions over time in a reduced complexity setup using tubing from different providers

Using a reduced complexity setup, we measured the development of effective flow and restoring force over a runtime of 12 hours. In almost all cases, the restoring force was significantly reduced over the course of 12 hours with the majority of the drop occurring during the first 4 hours regardless of the pump position (Figure 5 and Table 5).

The effective flow measurements revealed a more complex behavior than the restoring force analysis. (Figure 6 and Table 6). The 3/32" tubing showed a significant reduction in the effective flow in four out of five cases. Yet, even though 15 measurements were accumulated at each time point, the development over time was less monotonous as expected. Regarding the 1/8" tubing, an initial rise in effective flow during the first 2-4 hours was observed. A reason for this could be that the increased flexibility of the tubing following degradation supports the tubing compression and re-expansion in the relatively rigid, thick walled tubing. Note that the absolute value of restoring force was about twice as high for 1/8" tubing compared to 3/32" tubing (example for a 50 cm tubing segment after 0 hour in ABOVE configuration: Raumedic 3/32": 118.85 ± 2.63 N, Raumedic 1/8": 223.05 ± 6.15 N)

### 3.3 Examination of traces of material tearing after prolonged tubing use

For a first evaluation of potential traces of material tearing, we examined thin slices of fresh and 12 hours used tubing under a confocal microscope and found no evidence within the visible scale (Supporting Information S1).

### 4 DISCUSSION

#### 4.1 Variability of restoring force and effective flow measurements

The restoring force and effective flow of the tubing expressed some variability at each measurement time point. This was likely caused by the number of pump rotations set using a display without any decimals leading to a slight variation in the exact pump speed.

#### 4.2 Potential influence of fluid temperature on effective flow

The lack of temperature regulation in our first set of experiments caused a variation of fluid temperature during the measurements. This was caused, on the one hand, by heat generation from the moving mechanical parts and, on the other hand, by addition of relatively cooler fluid to readjust the reservoir to the expected filling. Yet, the temperature

---

**TABLE 5** Means and standard deviations of relative restoring force values at different timepoints using various tubing sets in both pump configurations

|          | Restoring force [%] | 0 hour  | 2 hours  | 4 hours  | 8 hours  | 12 hours | P value |
|----------|---------------------|---------|----------|----------|----------|----------|---------|
| Eurosets | ABOVE               | 100.0 ± 0.0 | 91.6 ± 1.7 | 85.5 ± 3.2 | 88.5 ± 1.4 | 88.7 ± 4.3 | <.001   |
| 3/32     | BELOW               | 100.0 ± 1.3 | 94.9 ± 0.4 | 92.0 ± 2.3 | 92.9 ± 1.7 | 88.0 ± 3.4 | <.001   |
| LivaNova | ABOVE               | 100.0 ± 2.6 | 93.4 ± 1.7 | 87.8 ± 4.0 | 86.4 ± 2.6 | 85.2 ± 1.9 | <.001   |
| 3/32     | BELOW               | 100.0 ± 1.2 | 96.0 ± 1.7 | 91.6 ± 1.9 | 91.3 ± 1.2 | 88.6 ± 1.8 | <.001   |
| Sorin    | ABOVE               | 100.0 ± 3.7 | 95.6 ± 1.1 | 95.4 ± 2.2 | 94.2 ± 2.4 | 94.5 ± 2.3 | <.001   |
| 3/32     | BELOW               | 100.0 ± 2.4 | 94.3 ± 2.1 | 92.9 ± 1.7 | 93.6 ± 2.5 | 92.3 ± 2.8 | <.001   |
| Medos    | ABOVE               | 100.0 ± 0.2 | 94.7 ± 2.2 | 96.8 ± 0.2 | 92.5 ± 0.3 | 92.5 ± 2.0 | <.001   |
| 3/32     | BELOW               | 100.0 ± 1.9 | 90.5 ± 2.8 | 90.7 ± 1.7 | 90.2 ± 1.5 | 88.3 ± 1.9 | <.001   |
| Raumedic | ABOVE               | 100.0 ± 2.3 | 94.6 ± 2.3 | 94.5 ± 2.2 | 89.7 ± 1.7 | 91.8 ± 2.2 | <.001   |
| 3/32     | BELOW               | 100.0 ± 1.9 | 99.6 ± 1.9 | 101.3 ± 0.9 | 100.8 ± 3.7 | 97.8 ± 2.9 | .093    |
| Raumedic | ABOVE               | 100.0 ± 1.5 | 95.4 ± 1.5 | 92.9 ± 1.5 | 92.9 ± 1.0 | 92.2 ± 1.2 | <.001   |
| 1/8 -LT  | BELOW               | 100.0 ± 1.0 | 93.7 ± 3.6 | 86.8 ± 1.4 | 86.2 ± 1.1 | 85.1 ± 1.2 | <.001   |
| Raumedic | ABOVE               | 100.0 ± 2.8 | 93.1 ± 1.3 | 95.0 ± 2.2 | 93.3 ± 1.6 | 91.4 ± 1.1 | <.001   |
| 1/8      | BELOW               | 100.0 ± 1.9 | 96.9 ± 2.3 | 94.6 ± 3.1 | 94.0 ± 2.0 | 88.9 ± 3.5 | <.001   |

*Note: Significance of trend tested by correlation for paired samples (Kendall’s tau). Restoring force raw data are given in Supporting Information S2.*
The difference between compared configurations was in the range of 0.4 to 0.7 °C (Table 7), with the BELOW measurements being performed at a lower temperature than the ABOVE measurements and an increase in temperature with experiment time.

To examine if this had an influence on the reported results regarding tubing age, we tested correlations between temperature and effective flow using Kendall’s tau. We found a negative correlation in the ABOVE ($\tau = -0.231$, $P < .001$) and a positive correlation in the BELOW configuration ($\tau = 0.146$, $P < .027$) and no significant correlation looking at the complete data set ($\tau = 0.003$, $P = .936$). The different direction of the correlation in both configurations and the small temperature difference between measurements at both tubing ages supports that the significantly lower effective flow reported after prolonged use (see Figure 4) was not caused by these temperature differences. Yet, we cannot rule out that they influenced the size of the effect.

Our experiments support four general recommendations regarding the use of ECC:

4.3 Modification of the ECC setup to the BELOW configuration

We could demonstrate that a modified ECC setup with the pump positioned below the level of the reservoir outlet leads to a significant reduction if not outright elimination of negative pressure values in the system. Since the suction forces corresponding to these negative pressure values might
mechanically strain and damage the corpuscular components, our experiments support a recommendation of the BELOW configuration of the ECC setup.

4.4 | Inclusion of flow sensors at the tubing after the roller pump

Our numerous measurements proved that the flow values measured in the tubing behind the roller pump did not reach the values adjusted at the ECC. This might be caused by slight deviations from the ideal fully expanded tubing assumed for the calculation of flows at the roller pump (Figure 1). Even though only a small amount of flow is lost our data underline the advantage of using flow sensors at the tubing behind the roller pump instead of only relying on the adjustment at the ECC instrumentation.

4.5 | ECC tubing shows aging and degradation over the course of 12 hours

The prolonged use and repeated compression of tubing leads to a significant reduction of its restoring force. This reduction correlates with—and as we hypothesize causes—a further reduction of effective flow over time which seems to be most pronounced within the first 4 hours of use. Taken together this might lead to two different approaches regarding tubing degradation. First it might be advisable to reduce the number of compression cycles for example by shortening the priming length or keeping the ECC on standby when possible. Alternatively it might be a valid approach to “preage” the tubing before use. Thus, the most pronounced degradation phase of the first 4 hours could be passed to reach more time consistent tubing properties for the use in the operating room. However, the latter approach does not seem feasible due to the time limits for tubing usage.

4.6 | Further research on the cause of restoring force reduction is necessary

So far it remains to be examined if the loss in restoring force is caused by stress-induced restructuring within the material, the dissociation of specific chemicals or a loss of particles through tearing. The latter case would have serious implications for

| TABLE 6 | Means and standard deviations of effective flow values at different timepoints using various tubing sets in both pump configurations |
| --- | --- | --- | --- | --- | --- | --- |
| | 0 hour | 2 hours | 4 hours | 8 hours | 12 hours | P value |
| Eurosets ABOVE | 96.4 ± 0.3 | 95.8 ± 0.3 | 95.3 ± 0.2 | 95.3 ± 0.3 | 94.8 ± 0.1 | <.001 |
| 3/32 BELOW | 95.9 ± 0.4 | 97.0 ± 0.2 | 95.9 ± 0.3 | 96.3 ± 0.1 | 95.6 ± 0.2 | .004 |
| LivaNova ABOVE | 99.9 ± 0.3 | 97.7 ± 0.3 | 96.6 ± 0.3 | 95.9 ± 0.3 | 95.2 ± 0.3 | <.001 |
| 3/32 BELOW | 96.9 ± 0.2 | 97.9 ± 0.3 | 97.2 ± 0.2 | 97.2 ± 0.3 | 97.1 ± 0.3 | .334 |
| Sorin ABOVE | 94.0 ± 0.2 | 94.4 ± 0.2 | 92.6 ± 0.3 | 91.5 ± 0.3 | 92.2 ± 0.3 | <.001 |
| 3/32 BELOW | 98.9 ± 0.7 | 98.0 ± 0.4 | 98.7 ± 0.3 | 97.0 ± 0.3 | 95.5 ± 0.3 | <.001 |
| Medos ABOVE | 97.1 ± 0.2 | 95.2 ± 0.3 | 94.8 ± 0.3 | 94.4 ± 0.4 | 93.8 ± 0.2 | <.001 |
| 3/32 BELOW | 98.3 ± 0.3 | 97.8 ± 0.2 | 96.3 ± 0.4 | 96.6 ± 0.5 | 96.8 ± 0.3 | <.001 |
| Raumedic ABOVE | 95.9 ± 0.3 | 95.8 ± 0.3 | 96.3 ± 0.3 | 95.2 ± 0.3 | 96.0 ± 0.2 | .715 |
| 3/32 BELOW | 97.6 ± 0.2 | 98.0 ± 0.3 | 97.5 ± 0.3 | 97.1 ± 0.3 | 95.5 ± 0.3 | <.001 |
| Raumedic ABOVE | 96.0 ± 0.3 | 96.4 ± 0.3 | 97.4 ± 0.2 | 96.9 ± 0.3 | 96.6 ± 0.2 | .001 |
| 1/8 -LT BELOW | 93.2 ± 0.3 | 95.7 ± 0.2 | 94.6 ± 0.2 | 94.8 ± 0.3 | 94.1 ± 0.3 | .778 |
| Raumedic ABOVE | 96.5 ± 0.3 | 96.4 ± 0.3 | 96.0 ± 0.3 | 95.5 ± 0.3 | 96.2 ± 0.3 | <.001 |
| 1/8 BELOW | 93.0 ± 0.3 | 94.8 ± 0.4 | 94.6 ± 0.2 | 93.4 ± 0.3 | 93.5 ± 0.3 | .589 |

Note: Significance of trend tested by correlation for paired samples (Kendall’s tau). The corresponding absolute flow values are given in Supporting Information S2.

| TABLE 7 | Means and standard deviations of measurement temperature in the standard setup at different target flows |
| --- | --- | --- | --- |
| ABOVE | BELOW | P |
| 3 L/min | <1 hour | 25.7 ± 0.4°C | 25.1 ± 0.5°C | .002 |
| >4 hours | 26.2 ± 0.7°C | 25.5 ± 0.7°C | .005 |
| P | .0251 | .102 |
| 4.5 L/min | <1 hour | 25.8 ± 0.3°C | 25.2 ± 0.4°C | <.001 |
| >4 hours | 26.2 ± 0.7°C | 25.6 ± 0.7°C | .020 |
| P | .039 | .147 |
| 6 L/min | <1 hour | 25.7 ± 0.2°C | 25.2 ± 0.3°C | <.001 |
| >4 hours | 26.4 ± 0.8°C | 25.6 ± 0.6°C | .008 |
| P | .058 | .124 |

Note: Significance of differences between ABOVE and BELOW configuration are listed in the fifth column, significances between tubing used <1 hour and tubing used >4 hours are listed in the 3rd, 6th, and 9th row.
the safety of ECC tubing after prolonged use since torn out particles entering the small capillaries through the bloodstream could be a potential risk factor for infarct events. A first evaluation of potential traces of material tearing did not show any visible tears within the µm scale. This might give a hint that if particles are lost at all they would range in the sub-µm scale.

5 | CONCLUSION

Our experiments lead to three general conclusions for ECC operators:

1. Switching to a BELOW configuration reduces negative pressures and improves effective flow.
2. The effective flow reaching the patient might deviate significantly from the adjusted flow due to tubing degradation and other factors. Therefore, inclusion of transit time flow sensors in the setup should be mandatory in order to obtain correct flow values.
3. Tubing within the ECC is degrading. Therefore, the runtime of the used setup should be kept at a sensible minimum.

ACKNOWLEDGMENT

Confocal microscopy images (Supporting Information S1) were performed at the Leibniz Institute for Zoo and Wildlife Research, Alfred-Kowalke-Straße 17, 10315 Berlin, Germany. The company Raumedic (Helmkrechts, Germany) supported this research with a grant as well as tubing samples.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest with the contents of this article.

AUTHOR CONTRIBUTIONS

Data analysis, Statistics, Drafting article: Schröter

Concept/Design: Müller

Data collection: Schröter, Müller

Critical revision of article: Müller, Hartrumpf, Ostovar, Kühnel, Albes

ORCID

Filip Schröter [ORCID ID]: https://orcid.org/0000-0002-9625-3066

REFERENCES

1. Tschaut RJ. Extrakorporale Zirkulation in Theorie und Praxis. 2nd ed. Lengerich, Germany: Pabst Science Publishers; 2005. p. 257–60.
2. Chumakova SP, Urazova OI, Novitskii VV, Shipulin VM, Mal’tseva IV, Khokhlov OA, et al. Factors of intravascular hemolysis in cardiosurgical patients after cardiopulmonary bypass procedures. Vestn Ross Akad Med Nauk. 2012;7:15–9.
3. Blackshear PL Jr, Dorman FD, Steinbach JH. Some mechanical effects that influence hemolysis. Trans Am Soc Artif Intern Organs. 1965;11:112–7.
4. Yeleswarapu K, Antaki J, Kameneva M. A mathematical model for shear-induced hemolysis. Artif Organs. 1995;19:576–82.
5. McCaughan JSJ, McMichael H, Schader JC, Kirby CK. The use of a totally occlusive pump as a flowmeter with observations on hemolysis caused by occlusive and nonocclusive pumps and other pump-oxygenator components. Surgery. 1958;44:210–9.
6. Murakami F, Usui A, Hiroura M, Kawamura M, Koyama T, Murase M. Clinical study of totally roller pumpless cardiopulmonary bypass system. Artif Organs. 1997;21:803–7.
7. Tamari Y, Lee-Sensiba K, Leonard EF, Tortolani AJ. A dynamic method for setting roller pumps nonocclusively reduces hemolysis and predicts retrograde flow. ASAIO J. 1997;43:39–52.
8. Tirilomis T, Tempes T, Waldmann-Beushausen R, Ballat C, Bensch M, Schoendube FA. Histological changes in neonatal kidneys after cardiopulmonary bypass and deep hypothermic circulatory arrest. Thorac Cardiovasc Surg. 2009;57:7–9.
9. Bernstein EF, Gleason LR. Factors influencing hemolysis with roller pumps. Surgery. 1967;61:432–42.
10. Xu S, Chen F, Ding M, Chen R, Lu S, Zhong H. The study of erythrocyte fragility and morphological changes caused by roller pump in vitro. Sheng Wu Yi Xue Gong Cheng Xue Za Zhi. 2002;19:419–22.
11. Chumakova SP, Urazova OI, Novitskii VV, Shipulin VM, Khokhlov OA, Emel’ianova TV, et al. Characteristic of the complement system in patients with ischemic heart disease with moderate and marked hemolysis after operations with cardiopulmonary bypass. Kardiologiia. 2013;53:4–9.
12. Mulholland JW, Massey W, Shelton JC. Investigation and quantification of the blood trauma caused by the combined dynamic forces experienced during cardiopulmonary bypass. Perfusion. 2000;15:485–94.
13. DeBakey M. A simple continuous-flow blood transfusion instrument. New Orleans Med Surg J. 1934;8:386–9.
14. Beck A. Zur Technik der Bluttransfusion. Klinische Wochenschrift. 1924;3:1999–2001.
15. Beck A. Über Bluttransfusion. Münchener Medizinische Wochenschrift. 1925;72:1232–6.
16. Knott E, Hahn A, inventors; Sorin Group Deutschland GmbH, assignee. Roller pump. Germany patent DE4327152C2. 1995.
17. R Core Team. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2020 [cited 2020 Nov 11]. Available from: https://www.R-project.org/
18. Holm S. A simple sequentially rejective multiple test procedure. Scand J Stat. 1979;6(2):65–70.
19. Müller T, Schröter F, Ostovar R, Kühnel RU. Vergleich unterschiedlicher Pumpenpositionen an der HLM. Kardiotechnik. 2018;3:74–81.

SUPPORTING INFORMATION

Additional Supporting Information may be found online in the Supporting Information section.

How to cite this article: Schröter F, Müller T, Hartrumpf M, Ostovar R, Kühnel R-U, Albes JM. Effects of tubing degradation and pump position on extracorporeal circulation performance. Artif Organs. 2021;45:E79–E88. https://doi.org/10.1111/aor.13847