Original Article
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Performance Characteristics of Hemofilters with Heparin Surface Coating: An Experimental Study
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Abstract
Heparin surface coated hemofilters and tubing sets were evaluated in comparison to identical but uncoated controls in 8 bovine experiments (74±6 kg). No heparin was given (neither systemically nor in the priming fluid). The hemofilters were primed with one liter of Ringer’s lactate in both groups and the maximal filter performance (arterial line pressure 300 mmHg; transmembrane pressure (TMP) 500 mmHg) was measured over 6 hours or until filter occlusion. All coated and one control filter remained functional during the scheduled 6 hours. The mean filter patency was 360±0 minutes for coated versus 210±99 minutes for uncoated (p<0.01). Mean blood flow at 1 hour and 6 hours was 675±114 and 580±96 ml/min for coated versus 432±183 and 25±43 for uncoated (NS; p<0.01). Mean filter output during the 6th hour and total filter output over 6 hours was 4225±998 ml and 21779±4273 for coated versus 400±692 and 7717±9757 for uncoated (p<0.01; p<0.01). Mean lactatedehydrogenase (LDH) levels before and 30 minutes after hemofiltration were 1855±413 IU and 2007±635 for coated versus 2160±411 and 1945±500 for uncoated (NS; NS). The heparin coated hemofilters demonstrated improved thromboresistance resulting in superior filter performance. There was no evidence of increased blood trauma.

Introduction
Hemofiltration (1) during and following cardiopulmonary bypass has proven to be an efficient tool for hemoconcentration in patients undergoing open heart surgery (2). However, the standard hemofilters available today still require a significant degree of anticoagulation to remain functional. Hence, at this time, perfusion with low or no systemic heparinization (3-5) precludes efficient hemofiltration. The present study was designed to evaluate the performance characteristics of heparin coated hemofilters without systemic heparinization.

Materials and Methods
Animals
Eight calves (74±6 kg bodyweight) were randomly assigned to two groups for hemofiltration either by heparin surface coated hemofilters and heparin coated tubing sets without systemic heparinization (coated) or standard uncoated hemofilters and tubing sets without systemic heparinization (uncoated). Following standardized premedication, general anesthesia was started with thiopental sodium and, after endotracheal intubation, maintained with nitrous oxide and halothane. All animals used in the study received humane
animal care in compliance with the "Guide for the Care and Use of Laboratory Animals," published by the National Institutes of Health (NIH Publication No. 85-23, revised 1985).

**Perfusion Equipment**

Hemofiltration equipment consisted of heparin surface coated\(^a\) hemofilters\(^b\) as well as heparin coated cannulas, PVC tubings, polycarbonate connectors and silicone pump loops for the study group (coated) whereas uncoated, but otherwise identical hemofilters and tubing sets were used for the control group (uncoated). A roller pump\(^c\) was used for both groups.

**Hemofiltration**

Hemofiltration was initiated in standard fashion. No heparin was given systemically. The hemofilters and tubing sets were primed with 1 L of Ringer's lactate and 1000 IU of heparin\(^d\). Following cervicotomy, the carotid artery and jugular vein were isolated and cannulated. The cannulas were connected

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\(^a\) Duraflo II, Baxter Bentley, Irvine, CA 92714  
\(^b\) Diafilter 30, Amicon, W. R. Grace & Co, Beverly, MA  
\(^c\) Stockert, Munich, Germany  
\(^d\) Liquemin, Roche, Basel, Switzerland
to the tubing sets and hemofiltration was started. Arterio-
venous hemofiltration with a roller pump proximal to the
hemofilter was selected to achieve maximum blood flow
(arterial line pressure 300 mmHg; transmembrane pressure
(TMP) 500 mmHg). Filter performance under these conditions
was measured over 6 hours or until filter occlusion. The
following parameters were analyzed: patency, filter pressure
gradient (blood path), TMP, blood flow, filter output, activated
cogulation time (ACT), hematocrit, and lactatedehydrogenase
(LDH)

Data Analyses
Mean and standard deviation was derived for each param-
eter analyzed in the two groups. Students t-test for unpaired
variables was used where applicable to determine statistical
significance of data: significance was defined at p<0.05.

Results
All coated hemofilters and one uncoated hemofilter re-
ained functional during the scheduled 6 hour study period.
Hence 0/4 coated versus 3/4 control filters occluded completely resulting in a mean patency (Figure 1) of 360±0 min for coated as compared to 210±99 for uncoated (p<0.01). Mean filter gradient (blood path) is depicted in Figure 2. It remained below 270 mmHg for coated whereas it increased above 300 mmHg (before the pump was stopped) for uncoated. Mean blood flow at 10 min and one hour was 895±187 ml/min and 675±114 ml/min for coated versus 712±123 ml/min and 432±183 ml/min for uncoated (NS; NS). Mean blood flow at 6 hours is depicted in Figure 3 and accounted for 580±96 ml/min for coated versus 25±43 ml/min for uncoated (p<0.01). Hemofilter output is depicted in Figure 4. During the first 10 minutes, 1625±419 ml were filtered with coated hemofilters as compared to 900±555 ml with uncoated hemofilters. Mean filter output during the 6th hour was 4225±998 ml for coated versus 400±692 ml for uncoated (p<0.01). Total filter output (Figure 5) over the 6 hour measuring period was 21779±4273 ml for coated as compared to 7717±9757 ml for uncoated. The ACT is depicted in Figure 6. The baseline value was 164±21 sec for coated as compared to 159±25 sec for uncoated (NS). At 6 hours the mean ACT was 163±16 sec for coated as compared to 261 sec for the only uncoated hemofilter still remaining patent. The evolution of the hematocrit is depicted in Figure 7. There is no difference between the two groups after cannulation: 31.7±4.9% for coated versus 32.6±1.3% for uncoated). However the value after 6 hours is significantly higher in the group perfused with heparin coated hemofilters (36.9±5.8% for coated versus 29.6±1.3% for uncoated). The hematocrit was even higher in the group perfused with heparin coated hemofilters that handled therefore successfully a larger cumulated blood cell mass with higher velocity. The constant thromboresistance of heparin coated perfusion equipment has been confirmed by other groups (7-9). However, a number of thromboresistant components are still lacking. Only recently, heparin coated cardiotomy reservoirs with improved thromboresistance and superior filter performance are a further step for development of extracorporeal life support with better biocompatibility. The potential benefits of thromboresistant perfusion equipment that have been shown in the experimental set-up with low or no systemic heparinization include superior hemostasis (3, 4), reduced blood loss (3,4), superior hemodynamics (4), better preservation of renal function and attenuated hormonal response (6). Improved thromboresistance of heparin coated perfusion equipment has been confirmed by other groups (7-9). However, a number of thromboresistant components are still lacking. Only recently, heparin coated cardiotomy reservoirs with improved thromboresistance became available (10). In the meanwhile, a number of clinical applications of heparin coated cardiopulmonary bypass equipment have been evaluated in selected cases with low systemic heparinization (5, 11). Under extreme conditions, i.e. accidental deep hypothermia with cerebral trauma, perfusion without systemic heparinization at all was successfully performed (12, 13). However, when the standard hemofilters used for reduction of serum potassium (14) were used with heparin coated cardiopulmonary bypass equipment without systemic heparinization, they had to be changed several times because of clotting. Hence, lack of

**Discussion**

Improved thromboresistance of heparin coated hemofilters results in superior filter performance. Improved thromboresistance of the heparin coated hemofilters is demonstrated in the present set-up by the absence of hemofilter occlusion during the 6 hour testing period with maximal blood flow. Only one filter of the control group remained patent for the full 6 hour test period. Thus mean duration of perfusion was significantly lower for uncoated devices (Figure 1). Progressive filter occlusion in the control group resulted also in an increasing filter gradient as measured for the blood path of the hemofilter (Figure 2). In contrast, the gradient for the heparin coated filters remained almost constant between 1 and 6 hours of perfusion. As a result of the increasing blood path gradient, the blood flow decreased in the control group and reached after 6 hours only 4.3% of the study group (Figure 3). Interestingly, hemofilter output was already superior for coated during the first 10 minutes when it reached 160% of uncoated (Figure 4). This finding suggests, that the heparin surface coating acted from the very beginning and that the protein layer built on the blood exposed heparin coated surfaces was different from uncoated devices. In the sixth hour, the output for coated hemofilters was tenfold that of uncoated controls. Hence filter output finally totaled after 6 hours, 21.8 L for coated as compared to 7.7 L for uncoated (Figure 5). This equalled over the 6 hour study period a mean filter output of 60 ml/min for coated as compared to 21 ml/min for uncoated. One can further speculate, that the not completely occluded uncoated hemofilter remained only patent because that specific animal had a prolonged activated coagulation time of more than 200 sec as shown in Figure 6. This could be due to contamination of the animal with a heparinized syringe used for blood gas sampling. The increased occlusion rate of uncoated hemofilters was not due to a difference of hematocrit for the two studied groups as shown in Figure 7. The hematocrit was even higher in the group perfused with heparin coated hemofilters that handled therefore successfully a larger cumulated blood cell mass with higher velocity. The constant LDH levels observed for the study group (Figure 8) demonstrate further that there was no major blood trauma despite maximized hemofiltration with blood flows above 500 ml/min for 6 hours in this group. The decrease of the LDH level observed for the control group after 5 hours can be attributed to increasing hemodilution which resulted from decreasing hemofiltration in this group. Hence, heparin coated hemofilters provide superior filter performance without measurable increase of blood trauma. Heparin coated hemofilters with improved thromboresistance and superior filter performance are a further step for development of extracorporeal life support with better biocompatibility. The potential benefits of thromboresistant perfusion equipment that have been shown in the experimental set-up with low or no systemic heparinization include superior hemostasis (3, 4), reduced blood loss (3,4), superior hemodynamics (4), better preservation of renal function and attenuated hormonal response (6). Improved thromboresistance of heparin coated perfusion equipment has been confirmed by other groups (7-9). However, a number of thromboresistant components are still lacking. Only recently, heparin coated cardiotomy reservoirs with improved thromboresistance became available (10). In the meanwhile, a number of clinical applications of heparin coated cardiopulmonary bypass equipment have been evaluated in selected cases with low systemic heparinization (5, 11). Under extreme conditions, i.e. accidental deep hypothermia with cerebral trauma, perfusion without systemic heparinization at all was successfully performed (12, 13). However, when the standard hemofilters used for reduction of serum potassium (14) were used with heparin coated cardiopulmonary bypass equipment without systemic heparinization, they had to be changed several times because of clotting. Hence, lack of
thromboresistant hemofilters, proved to be a major problem in this situation and triggered further research. The development of thromboresistant hemofilters for clinical application is therefore a necessity that will improve not only hemofiltration in patients undergoing cardiopulmonary bypass but also in patients with bleeding problems after cardiothoracic surgery, general surgery, major trauma or long term hemofiltration (15, 16) in general.

References