

A Convertible Cardiopulmonary Bypass System for Optimized Hemofiltration

Ludwig von Segesser, MD, Eligio Garcia, BA, Mario Lachat, MD, Marko Turina, MD

Clinic for Cardiovascular Surgery, University Hospital
Zurich, Switzerland

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Abstract

Hemofiltration during or after cardiopulmonary bypass has proved to be an efficient tool for hemoconcentration. Classically, the hemofilters are supplied by the arterial line and the filtration rate is mainly a function of the perfusion pressure. We have developed a convertible cardiopulmonary bypass system including a double head roller pump for blood cardioplegia application that allows optimized hemofiltration independent from systemic perfusion. Serial bench studies were performed at normothermia with a mean hematocrit of 20%, and identical hemofilters:

	CLASSIC	OPTIMIZED	p<
Systemic pump flow l/min	3.5±0.9	3.5±0.9	NS
Arterial line pressure mmHg	148±3	135±8	0.05
Filter line pressure mmHg	144±8	378±30	0.05
Filter flow ml/min	152±3	346±6	0.05
Filter output ml/15 min	999±228	1599±174	0.05

Hemofiltration can be optimized by a convertible cardiopulmonary bypass system allowing independent hemofilter-flow adjustment. Improved results were confirmed in routine clinical application.

Introduction

Hemofiltration (1) during or after cardiopulmonary bypass has proven to be an efficient tool for hemoconcentration in patients undergoing open heart surgery. The filtrate formed in hemofiltration quantifies solute removal in a way similar to primary urine (2). The filtration rate of the hemofilters is, for a given clinical situation and a given membrane, mainly a function of blood flow and transmembrane pressure (TMP). Classically, the hemofilters are supplied with blood by the arterial line of the cardiopulmonary bypass (CPB). In this case the filtration rate becomes mainly a function of the arterial line pressure. As the latter is low during various periods of the perfusion, poor filtration may result. The present study was designed to evaluate a convertible cardiopulmonary bypass system including a double head roller pump for blood

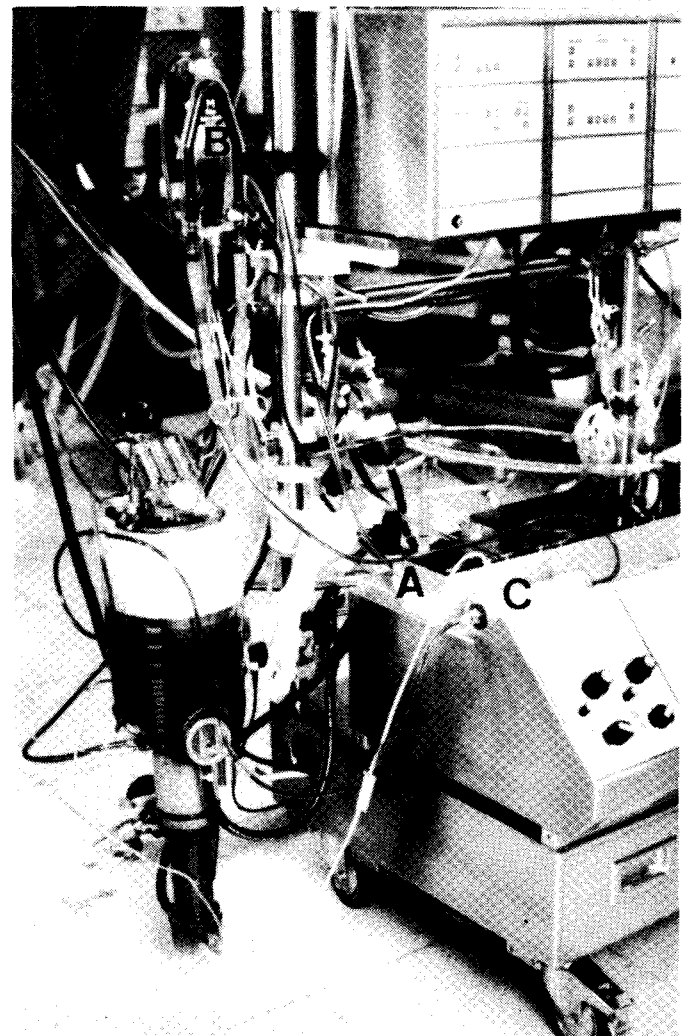
*Address correspondence to: Ludwig K. von Segesser, M.D.,
Clinic for Cardiovascular Surgery, University Hospital, CH-
8091 Zurich, Switzerland.*

cardioplegia application that allows optimized hemofiltration independent from systemic perfusion.

Patients, Materials, and Methods

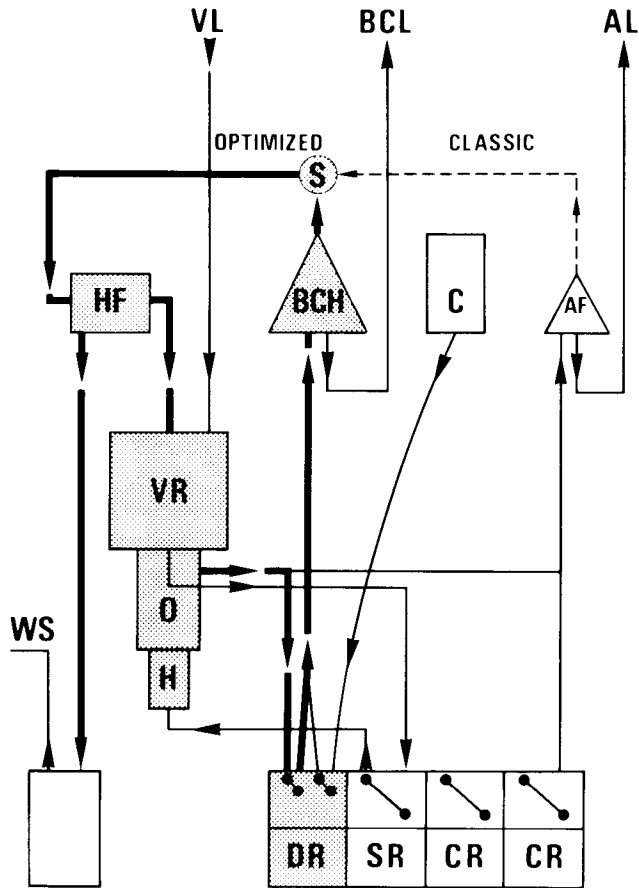
The present study was realized with a computer aided modular perfusion system (CAPS, Stockert Shiley, Munich, Federal Republic of Germany) including a multiflow roller

FIGURE 1: Heart lung machine equipped with double head rollerpump (A) for combined blood cardioplegia application and OPTIMIZED hemofiltration including blood cardioplegia heat exchanger (B) and hemofilter (C)



pump for systemic perfusion, two multifold roller pumps for cardiomy suction and a double head roller pump for blood cardioplegia application and hemoconcentration (Figure 1). With the latter, an infinitely variable blood/crystalloid solution cardioplegia proportion can be fixed (e.g. 1:1) in the "Master-Slave" mode and infused. However direct control allows also infinitely variable flow rates of either blood or crystalloid solution (cardioplegia). Therefore connection of the hemofilter between the venting stopcock of the blood cardioplegia heat exchanging device and the venous reservoir of the oxygenator (D 703 Compactflo, Dideco, Mirandola, Italy) (3, 4) allows to realize fast priming of the hemofilter with crystalloids (excess priming fluid should be discarded if heparinized crystalloid cardioplegia solution is used) as well as optimized filtration with independent hemofilter line pressures and flow rates. The schematic set-up for optimized as well as for classic hemofiltration is shown in Figure 2.

FIGURE 2: Schematic set-up of the convertible cardiopulmonary bypass system for OPTIMIZED and CLASSIC hemofiltration including venous line (VL), venous reservoir (VR), systemic roller pump (SR), heat exchanger (H), oxygenator (O), arterial filter (AF), arterial line (AL), double head roller pump (DR, blood cardioplegia heat exchanger (BCH), crystalloid cardioplegia solution (C), blood cardioplegia line (BCL), hemofilter (HF), stop-cock (S), wall suction (WS) and cardiotomy roller pumps (CR)



Bench Tests

Serial bench studies were performed with the set-up described above and a polyamid hollow fiber hemofilter (FH 55, Gambro AB, Lund, Sweden). This filter includes 6200 hollow fibers with an internal diameter of 215 μm (dry and wet) and an effective length of 140 mm. The effective membrane area accounts for 0.6 m^2 . The priming volume is 43 ml. For this study, the hemofilters were connected with a three-way stop-cock alternatively to the arterial filter for classic hemofiltration and to the blood cardioplegia heat exchanger for optimized hemofiltration (Figure 2). Human blood was used at normothermia (37°C) and a hematocrit of 20%. Flow provided by the systemic pump, arterial line pressure, filter line pressure, transmembrane pressure (TMP), filter flow, filter output, temperatures and increase of hematocrit were analyzed.

Clinical Studies

Optimized hemofiltration was analyzed in a series of 100 patients age 54 ± 19 undergoing cardiopulmonary bypass (mean body weight 67 ± 16 kg) for coronary artery revascularization ($n=38$), aortic valve replacement ($n=20$), mitral valve repair or replacement ($n=10$), heart transplantation ($n=10$) and others ($n=22$). Duration of perfusion, total amount of filtrate as well as hematocrit before and after hemofiltration were analyzed.

Data Analyses

The flows, pressures and temperatures were recorded simultaneously by the computer aided perfusion system. All values are expressed as mean \pm standard deviation. Students t-test (paired or unpaired) was used where applicable for determination of statistical significance ($p < 0.05$).

Bench Tests

For a similar mean systemic pump flow in both groups (3.5 ± 0.9 l/min) an arterial line pressure of 148 ± 3 mmHg was measured for classic versus 135 ± 8 mmHg for optimized hemofiltration ($p < 0.05$). The hemofilter blood inlet pressure achieved was 144 ± 8 mmHg for classic versus 378 ± 30 mmHg for optimized ($p < 0.05$) as shown in Figure 3. Figure 4 shows the TMP achieved for classic was 539 ± 9 mmHg versus 713 ± 74 mmHg for optimized ($p < 0.05$). Hemofilter blood flow was 152 ± 3 ml/min for classic versus 346 ± 6 ml/min for optimized ($p < 0.05$) as depicted in Figure 5. Figure 6 shows the filtrate generated over 15 minutes which was 999 ± 228 ml for classic versus 1599 ± 174 ml for optimized ($p < 0.05$) or normalized, 67 ± 12 ml/min for classic versus 107 ± 12 ml/min for optimized ($p < 0.05$). Over five minutes, a mean increase in hematocrit of $3.3 \pm 0.4\%$ was achieved in for classic versus $4.5 \pm 0.5\%$ for optimized ($p < 0.05$).

Clinical Results

Optimized hemofiltration in the clinical set-up showed the following results for the 100 analyzed patients: Mean duration of cardiopulmonary bypass was 87 ± 49 minutes. The total amount of filtrate collected with optimized hemofiltration was 1477 ± 862 ml. Despite application of multidose cardioplegia in

FIGURE 3: Hemofilter blood inlet pressure for CLASSIC and OPTIMIZED (mean \pm standard deviation)

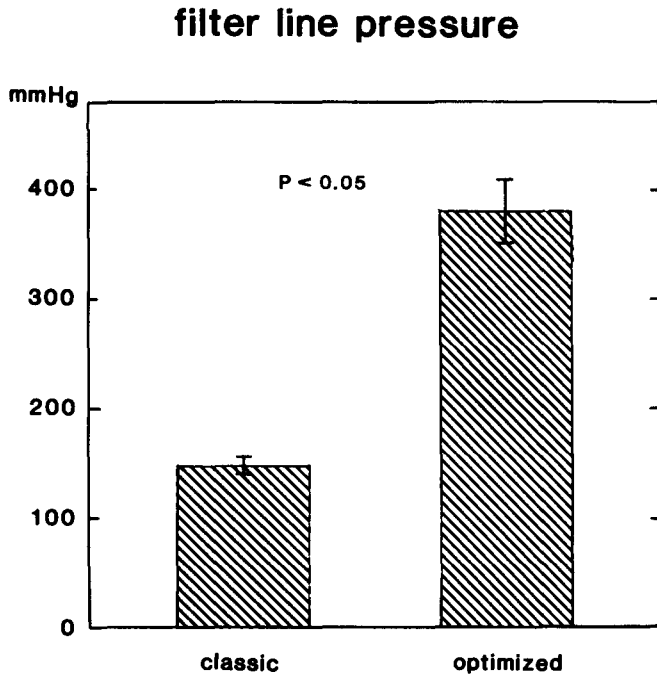


FIGURE 4: Transmembrane pressure for CLASSIC and OPTIMIZED (mean \pm standard deviation)

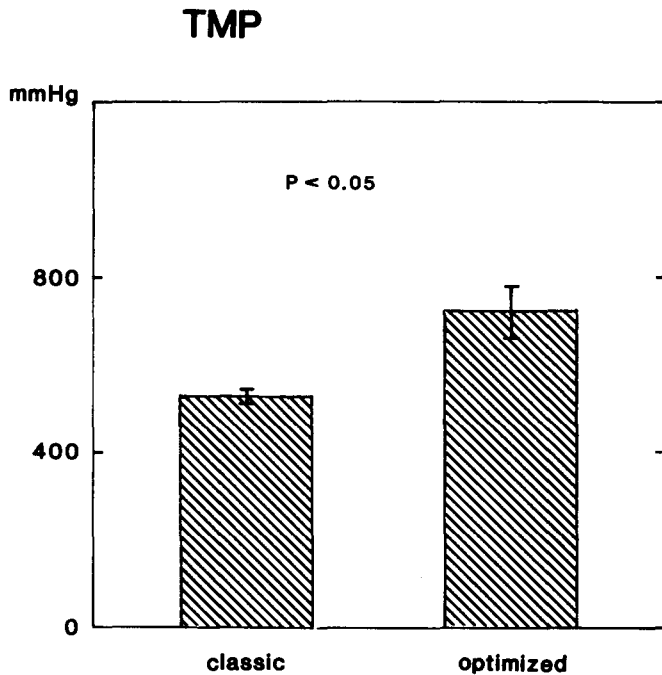


FIGURE 5: Hemofilter blood flow for CLASSIC and OPTIMIZED (mean \pm standard deviation)

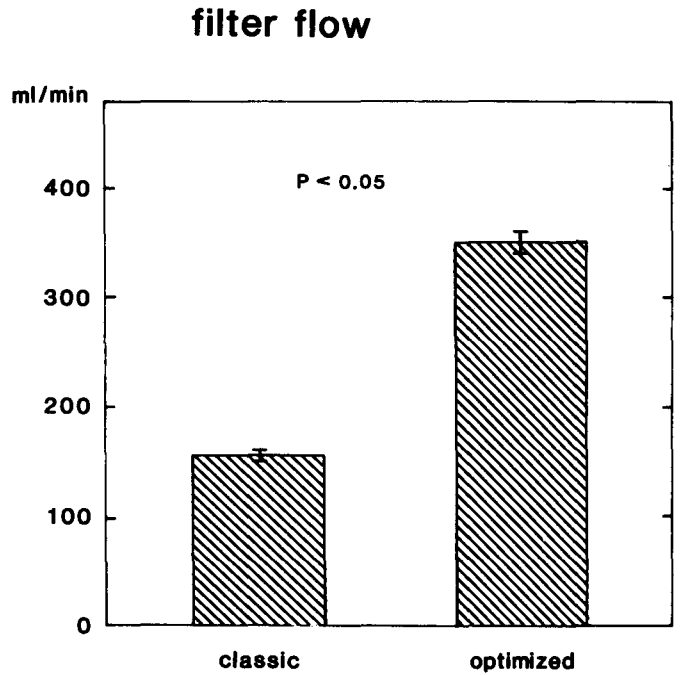
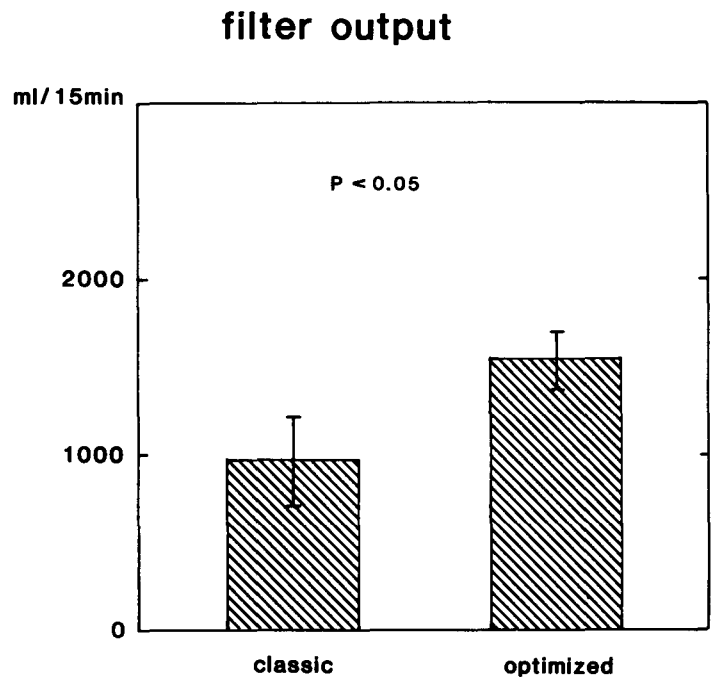


FIGURE 6: Filtrate volume achieved over 15 minutes for CLASSIC and OPTIMIZED (mean \pm standard deviation)



90/100 cases (no cardioplegia was given for transplantation) mean hematocrit increased (all patients) from $22.0 \pm 3.6\%$ before hemofiltration to $24.5 \pm 3.5\%$ after hemofiltration ($p < 0.05$). No set-up or device related complication occurred in this series of 100 cases.

Discussion

Optimized hemofiltration can be realized in the clinical setting of open heart surgery with a convertible cardiopulmonary bypass system using the double head blood cardioplegia roller pump for rapid priming of the hemofilter with crystalloids and independent hemofilter blood flow adjustment. In the set-up

depicted in Figure 2, a standardized hemofilter set can be added onto the standard perfusion set during perfusion without any interruption of the systemic blood flow. The connection of the hemofilter to the venting port of the blood cardioplegia heat exchanger and the venous line to the cardiectomy reservoir does not interfere with the routine set-up of the heart lung machine. For a given systemic pumpflow of 3.5 l/min our bench tests have shown for optimized hemofiltration that the blood path of the double head blood cardioplegia roller pump allows to generate a higher hemofilter inlet pressure which accounts for 263% of the pressure generated by the systemic pump in classic hemofiltration. This difference allows for optimized to achieve a higher TMP (132%) as well as a higher hemofilter blood flow (227%) resulting in a higher filtrate volume of 160% of the volume achieved over the same time period with classic hemofiltration. Hence there is also a higher increase of hematocrit or more hemoconcentration for optimized. The superiority of optimized hemofiltration appears to be even more striking in clinical application during perfusion with low arterial line pressures at low temperatures. Under these circumstances the hemofilter blood flow drops dramatically in classic hemofiltration and consecutively the filtration rate is poor whereas high TMP, high filter blood flow and efficient hemoconcentration can be maintained by optimized hemofiltration. Although high TMP was evaluated during the bench tests, we have to mention here, that the maximum TMP recommended by the manufacturer for the hemofilter used is 600 mmHg. Taking in account the high efficiency of optimized hemofiltration a TMP of 500 mmHg or less was adequate in all clinical cases. There can be no doubt about the clinical benefits of hemofiltration which have also been documented for long-term application (5, 6). The clinical series of acute hemofiltration during open heart surgery in 100 cases presented here, shows furthermore that optimized hemofiltration with the described convertible cardiopulmonary bypass system is safe.

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