Factors influencing the individual effects of blood transfusions on oxygen delivery and oxygen consumption*

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**Objective:** To determine factors influencing the individual effects of blood transfusions regarding oxygen delivery and consumption.

**Design:** Chart review.

**Setting:** A university hospital cardio-surgical intensive care unit.

**Patients:** Sixty-seven patients with 170 transfusion events evaluated.

**Interventions:** Blood transfusion.

**Measurements and Main Results:** Measurements were performed before and after a blood transfusion, separated by 302 ± 13 mins (mean ± SEM). The individual increase in cardiac index resulting from a blood transfusion was inversely related to cardiac index before transfusion (p < .001), oxygen delivery index before transfusion (p < .001), and oxygen consumption index before transfusion (p < .001). The individual increase in oxygen delivery index was inversely related to oxygen consumption index before transfusion (p < .001). The individual increase in oxygen consumption index was inversely related to oxygen consumption index before transfusion (p < .001). Individual changes in cardiac index, oxygen delivery index, and oxygen consumption index were not significantly related to preoperative ejection fraction (25%–87%), age (32–81 yrs), and pretransfusion hemoglobin concentration (5.0–11.8 g/dL).

**Conclusion:** In adult patients after cardiovascular surgery, oxygen delivery- and oxygen consumption-related variables predict the individual response to blood transfusions better than do patient characteristics such as preoperative ejection fraction, age, and pretransfusion hemoglobin concentration. Including oxygen delivery and oxygen consumption, variables into the transfusion decision, thus, may enable a more individual use of allogeneic blood in specific situations. (Crit Care Med 1999; 27:2194 – 2200)

**Key Words:** red blood cell transfusion; oxygen delivery; oxygen consumption; cardiac index; preoperative ejection fraction; age; hemoglobin concentration; adult cardiac surgery; postoperative treatment; individual response

The effects of allogeneic blood transfusions on hemodynamics, oxygen delivery, and oxygen consumption are not well defined in critically ill patients (1). There are only a few studies (2–12), with relatively small populations, published. These studies are consistent regarding the increase in oxygen delivery, but the effects on oxygen consumption and hemodynamics were variable (1). In addition, it appears impossible at present to predict, in an individual patient, whether oxygen consumption will increase in response to a blood transfusion (13, 14). We, thus, performed the present investigation to assess these effects in a larger population of patients after cardiovascular operations with a wide range of pretransfusion hemoglobin concentrations and, in particular, to study whether specific factors related to the condition before a blood transfusion might influence the individual response to allogeneic blood transfusions.

**MATERIALS AND METHODS**

The charts of all patients with a pulmonary artery catheter, who were treated in the cardio-surgical intensive care unit at the University Hospital Zürich during a 12-month study period (May 1, 1994 through April 30, 1995), were prospectively analyzed. No approval by the Internal Review Board was mandated at the University Hospital Zürich for an exclusive chart review study. This time period was chosen because, beginning on November 1, 1994, blood transfusion guidelines were altered, such that the hematocrit at which a blood transfusion was advised was decreased by 5% (from a hematocrit of 25% in patients with a preoperative ejection fraction >40% without major catecholamine requirement and a hematocrit of 30% for patients with a preoperative ejection fraction of <40% and/or major catecholamine requirement to 20% and 25%, respectively). This enabled us to study a wide range of pretransfusion hemoglobin concentrations. Blood was administered in the form of packed red cells with a hematocrit of 60% ± 5%. When an allogeneic blood transfusion was administered and a complete set of hemodynamic variables as well as arterial and mixed venous blood gases were recorded before and after the blood transfusion, this transfusion event was eligible for the study. A complete set of hemodynamic variables consisted of mean arterial pressure, mean pulmonary artery pressure, central venous and pulmonary capillary wedge pressures, cardiac output (thermodilution using three 10-mL iced saline injections), and heart rate. On the basis of the above primary data, cardiac index, stroke volume index, systemic and pulmonary...
vascular resistances, oxygen delivery index, oxygen consumption index, oxygen extraction ratio, and arteriovenous oxygen difference were computed according to standard formulas. The following variables were additionally recorded: volume of transfused blood, volume of concomitantly infused colloids, volume of concomitant blood loss, infusion rates of dopamine, dobutamine, epinephrine, norepinephrine, nitroglycerin, phentolamine (α-adrenergic blocker), body temperature, number of days treated in the intensive care unit, and hemoglobin concentration. Pre- and posttransfusion measurements were separated by 302 ± 13 mins (mean ± SEM).

Transfusion events with incomplete data sets were excluded from data analysis. To characterize the effects of a blood transfusion as purely as possible without being influenced by the effects of concomitant therapy, transfusion events with concomitant colloid infusions >300 mL; with changes in dopamine, dobutamine, nitroglycerin, or phentolamine infusion rates >50 μg/min; or with a change in epinephrine or norepinephrine infusion rate >1 μg/min were additionally excluded from final data analysis.

Data were analyzed to answer two questions. First, what are the global effects of allogeneic blood transfusions? Second, which factors related to the condition before a blood transfusion influence the response to allogeneic blood transfusions in terms of oxygen delivery and consumption? To answer the first question, group mean changes resulting from allogeneic blood transfusions were analyzed using paired Student’s t-tests (Statview 4.51, Abacus Concepts, Berkeley, CA). To answer the second question, individual changes in cardiac index, oxygen delivery index, and oxygen consumption index resulting from a blood transfusion were related to a variety of variables using simple linear regression analyses with Bonferroni correction and forward stepwise regression analyses (p < .05) (Statview 4.51, Abacus Concepts). These variables were age, preoperative ejection fraction, body surface area, postoperative day, volume of transfused blood, volume of concomitantly infused colloids, volume of concomitant blood loss, and pretransfusion variables, which comprised heart rate; mean arterial pressure; central venous and pulmonary capillary wedge pressures; infusion rates of dobutamine, epinephrine, norepinephrine, dopamine, nitroglycerin, and phentolamine; arterial oxygen partial pressure; arterial and venous hemoglobin saturation; base excess; hemoglobin concentration; cardiac index; oxygen delivery index; oxygen consumption index; oxygen extraction ratio; and arteriovenous oxygen difference. Data are given as mean ± SEM.

RESULTS

During the 12-month study period, 754 patients with a pulmonary artery catheter were treated in the cardio-surgical intensive care unit. Of these, 407 patients received an allogeneic blood transfusion and had complete data sets recorded before and after a blood transfusion. Because of the restrictions described above, which were aimed at characterizing the effects of blood transfusions as purely as possible without being influenced by the effects of concomitant therapy, 170 transfusion events from 67 patients were entered into the final data analysis. Patient characteristics are given in Table 1. Transfusions were performed at postoperative day 1.6 ± 0.2. The volume of blood transfusions was 368 ± 10 mL administered over 302 ± 13 mins. Concomitant blood loss was 146 ± 13 mL, and concomitant colloid administration was 105 ± 9 mL.

Global Effects of Allogeneic Blood Transfusions. Allogeneic blood transfusion increased the hemoglobin concentration from 8.1 ± 0.1 to 9.0 ± 0.1 g/dL. Filling pressure, however, was unchanged (Table 2). Mean arterial and mean pulmonary artery pressure increased slightly as a result of a blood transfusion. The heart rate remained stable. Cardiac index was unchanged. Systemic vascular resistance was stable, and pulmonary vascular resistance increased as a result of a blood transfusion (Table 2). Oxygen delivery index increased, however, without an increase in oxygen consumption index. Therefore, oxygen extraction ratio decreased, which resulted in a slightly increased mixed venous oxygen saturation (Table 2). Arteriovenous oxygen difference increased during a blood transfusion. Paco2 increased, pH and base excess were stable, and PaO2 and arterial oxygen saturation decreased during a blood transfusion. Body temperature was slightly higher after a blood transfusion than before. Dopamine, dobutamine, epinephrine, and norepinephrine infusion rates were similar before and after a blood transfusion (Table 2). In addition, phentolamine infusion rate was unchanged, and nitroglycerin infusion rate decreased minimally.

Factors Influencing Individual Responses in Oxygen Delivery and Consumption Resulting from Allogeneic Blood Transfusions. The results of simple linear regression analyses relating individual changes in cardiac index, oxygen delivery index, and oxygen consumption index to a variety of factors are summarized in Table 3. Infusion rates of dopamine, dobutamine, epinephrine, norepinephrine, phentolamine, and nitroglycerin before a blood transfusion did not influence these individual responses (data not shown).

The individual change in cardiac index resulting from a blood transfusion was significantly correlated with the pretransfusion cardiac index, oxygen consumption index, oxygen delivery index, and arterial oxygen saturation, as well as the volume of concomitantly infused colloids (Table 3; Fig. 1). Stepwise linear regression analysis confirmed pretransfusion cardiac index as the most significant independent factor determining the individual change in cardiac index resulting from a blood transfusion (Table 4). Pretransfusion mixed venous oxygen saturation and pretransfusion dobutamine infusion rate were found to be additional independent factors influencing the individual change in cardiac index resulting from a blood transfusion, although the individual change in cardiac index was not significantly related to these variables in simple linear regression analyses.

The individual change in oxygen delivery is given in Table 3. Patients were divided into four groups according to their individual change in cardiac index. The mean ± SEM and range or percentage of individual changes in selected variables, which were significantly related to the individual change in cardiac index, are given in Table 4.

Table 1. Patient characteristics (n = 67): Mean ± SEM and range or percentage

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean ± SEM</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>61 ± 1</td>
<td>32–81</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>72 ± 2</td>
<td>48–114</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>167 ± 6</td>
<td>138–194</td>
</tr>
<tr>
<td>BSA (m²)</td>
<td>1.8 ± 0.1</td>
<td>1.3–2.4</td>
</tr>
<tr>
<td>LV EF (%)</td>
<td>57 ± 2</td>
<td>25–87</td>
</tr>
<tr>
<td>ASA III/IV</td>
<td>2/65</td>
<td></td>
</tr>
<tr>
<td>F/M</td>
<td>26/41</td>
<td></td>
</tr>
<tr>
<td>Preop. β-blockers (n, %)</td>
<td>35/67 (52)</td>
<td></td>
</tr>
<tr>
<td>Preop. Ca channel blockers (n, %)</td>
<td>19/67 (28)</td>
<td></td>
</tr>
<tr>
<td>Preop. nitrates (n, %)</td>
<td>32/67 (48)</td>
<td></td>
</tr>
<tr>
<td>Preop. diuretics (n, %)</td>
<td>23/67 (34)</td>
<td></td>
</tr>
<tr>
<td>Preop. ACE inhibitors (n, %)</td>
<td>23/67 (34)</td>
<td></td>
</tr>
<tr>
<td>Preop. digoxin (%)</td>
<td>14/67 (21)</td>
<td></td>
</tr>
</tbody>
</table>

BSA, body surface area; LV EF, left ventricular ejection fraction; ASA III/IV, number of patients of ASA class III and IV; F/M, number of female and male patients; Preop. β-blockers, preoperative treatment with β-adrenergic blockers; Preop. Ca channel blockers, preoperative treatment with calcium channel blockers; Preop. nitrates, preoperative treatment with nitrates on a fixed schedule; Preop. diuretics, preoperative treatment with diuretics; Preop. ACE inhibitors, preoperative treatment with angiotensin-converting enzyme inhibitors; Preop. digoxin, preoperative treatment with digoxin.

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### Table 2. Hemodynamics, oxygenation, oxygen transport, and oxygen consumption before and after an allogeneic blood transfusion (n = 170)

<table>
<thead>
<tr>
<th></th>
<th>Before Blood Transfusion</th>
<th>After Blood Transfusion</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hb (gm/dL)</td>
<td>8.1 ± 0.1</td>
<td>9.0 ± 0.1</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>PCWP (mm Hg)</td>
<td>9.7 ± 0.3</td>
<td>10.2 ± 0.3</td>
<td>.092</td>
</tr>
<tr>
<td>CVP (mm Hg)</td>
<td>8.9 ± 0.3</td>
<td>8.9 ± 0.3</td>
<td>.884</td>
</tr>
<tr>
<td>MAP (mm Hg)</td>
<td>71.1 ± 0.6</td>
<td>72.9 ± 0.7</td>
<td>.010</td>
</tr>
<tr>
<td>MPAP (mm Hg)</td>
<td>18.5 ± 0.5</td>
<td>20.0 ± 0.5</td>
<td>.002</td>
</tr>
<tr>
<td>HR (beats/min)</td>
<td>96.2 ± 1.1</td>
<td>95.8 ± 1.1</td>
<td>.622</td>
</tr>
<tr>
<td>SVR (dynes/cm²)</td>
<td>920 ± 20</td>
<td>951 ± 19</td>
<td>.069</td>
</tr>
<tr>
<td>PVR (dynes/cm²)</td>
<td>135 ± 6</td>
<td>149 ± 6</td>
<td>.017</td>
</tr>
<tr>
<td>CI (L/min·m²)</td>
<td>3.2 ± 0.1</td>
<td>3.1 ± 0.1</td>
<td>.486</td>
</tr>
<tr>
<td>DO₂ (mL/min·m²)</td>
<td>357 ± 8</td>
<td>386 ± 8</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>VO₂ (mL/min·m²)</td>
<td>124 ± 2</td>
<td>127 ± 2</td>
<td>.067</td>
</tr>
<tr>
<td>O₂-Ex. (%)</td>
<td>35.9 ± 0.7</td>
<td>34.2 ± 0.6</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>AVD-DO₂ (mL/dL)</td>
<td>6.0 ± 0.1</td>
<td>4.2 ± 0.1</td>
<td>.004</td>
</tr>
<tr>
<td>SVO₂ (%)</td>
<td>65.0 ± 0.6</td>
<td>65.0 ± 0.6</td>
<td>.404</td>
</tr>
<tr>
<td>PaO₂ (torr [kPa])</td>
<td>111 ± 3 (14.8 ± 0.4)</td>
<td>100 ± 2 (13.3 ± 0.3)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>SaO₂ (%)</td>
<td>96.8 ± 0.2</td>
<td>96.2 ± 0.2</td>
<td>.001</td>
</tr>
<tr>
<td>PaCO₂ (torr [kPa])</td>
<td>39 ± 1 (5.2 ± 0.1)</td>
<td>41 ± 1 (5.4 ± 0.1)</td>
<td>.022</td>
</tr>
<tr>
<td>pH</td>
<td>7.36 ± 0.01</td>
<td>7.36 ± 0.01</td>
<td>.358</td>
</tr>
<tr>
<td>BE (mmol/L)</td>
<td>-2.7 ± 0.2</td>
<td>-2.4 ± 0.2</td>
<td>.064</td>
</tr>
<tr>
<td>Dobutamine (µg/min)</td>
<td>102 ± 10</td>
<td>102 ± 10</td>
<td>.319</td>
</tr>
<tr>
<td>Epinephrine (µg/min)</td>
<td>1.3 ± 0.4</td>
<td>1.3 ± 0.4</td>
<td>.999</td>
</tr>
<tr>
<td>Noradrenaline (µg/min)</td>
<td>1.1 ± 0.3</td>
<td>1.1 ± 0.3</td>
<td>.707</td>
</tr>
<tr>
<td>Nitroglycerin (µg/min)</td>
<td>54 ± 5</td>
<td>48 ± 5</td>
<td>.001</td>
</tr>
<tr>
<td>Phenolamine (µg/min)</td>
<td>26 ± 5</td>
<td>26 ± 5</td>
<td>.873</td>
</tr>
<tr>
<td>Temperature (°F [°C])</td>
<td>98.78 ± 32.18 (37.1 ± 0.1)</td>
<td>99.14 ± 32.18 (37.3 ± 0.1)</td>
<td>.011</td>
</tr>
</tbody>
</table>

Data are mean ± SEM. Hb, hemoglobin concentration; PCWP, pulmonary capillary wedge pressure; CVP, central venous pressure; MAP, mean arterial pressure; MPAP, mean pulmonary artery pressure; HR, heart rate; SVR, systemic vascular resistance; MPAP, mean pulmonary artery pressure; CI, cardiac index; DO₂, oxygen delivery index; VO₂, oxygen consumption index; O₂-Ex., oxygen extraction ratio; AVDO₂, arteriovenous oxygen difference; SVO₂, mixed venous oxygen saturation; SaO₂, arterial oxygen saturation; BE, base excess.

*Significant p values.

### Table 3. p Values, coefficient of oxygen determination (R²), and regression coefficient (RC) among individual changes in cardiac index (CI diff), oxygen delivery index (DO₂ diff), and oxygen consumption index (VO₂ diff) resulting from a blood transfusion (n = 170) in relation to a variety of factors as assessed by simple linear regression analyses

<table>
<thead>
<tr>
<th></th>
<th>CI diff</th>
<th>DO₂ diff</th>
<th>VO₂ diff</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p</td>
<td>R²</td>
<td>RC</td>
</tr>
<tr>
<td>POD</td>
<td>.521</td>
<td>.002</td>
<td>inv</td>
</tr>
<tr>
<td>Vol. blood transfused</td>
<td>.796</td>
<td>.001</td>
<td>dir</td>
</tr>
<tr>
<td>Vol. blood loss</td>
<td>.214</td>
<td>.009</td>
<td>inv</td>
</tr>
<tr>
<td>Vol. colloid</td>
<td>.002</td>
<td>.055</td>
<td>dir</td>
</tr>
<tr>
<td>PCWP before</td>
<td>.325</td>
<td>.006</td>
<td>inv</td>
</tr>
<tr>
<td>CVP before</td>
<td>.261</td>
<td>.007</td>
<td>inv</td>
</tr>
<tr>
<td>MAP before</td>
<td>.284</td>
<td>.007</td>
<td>dir</td>
</tr>
<tr>
<td>HR before</td>
<td>.057</td>
<td>.026</td>
<td>inv</td>
</tr>
<tr>
<td>O₂-Ex. before</td>
<td>.917</td>
<td>&lt;.001</td>
<td>dir</td>
</tr>
<tr>
<td>AVDO₂ before</td>
<td>.767</td>
<td>&lt;.001</td>
<td>dir</td>
</tr>
<tr>
<td>SVO₂ before</td>
<td>.461</td>
<td>.003</td>
<td>dir</td>
</tr>
<tr>
<td>PaO₂ before</td>
<td>.014</td>
<td>.035</td>
<td>dir</td>
</tr>
<tr>
<td>SaO₂ before</td>
<td>.001</td>
<td>.070</td>
<td>dir</td>
</tr>
<tr>
<td>BE before</td>
<td>.082</td>
<td>.018</td>
<td>dir</td>
</tr>
</tbody>
</table>

POD, postoperative day; Vol. blood transfused, volume of blood transfused; Vol. blood loss, volume of concomitant blood loss; Vol. colloid, volume of concomitant colloid infused; PCWP before, pulmonary capillary wedge pressure before blood transfusion; CVP before, central venous pressure before blood transfusion; MAP before, mean arterial pressure before blood transfusion; HR before, heart rate before blood transfusion; O₂-Ex. before, oxygen extraction ratio before blood transfusion; AVDO₂ before, arteriovenous oxygen difference before blood transfusion; SVO₂ before, mixed venous oxygen saturation before blood transfusion; SaO₂ before, arterial oxygen saturation before blood transfusion; BE before, base excess before blood transfusion; inv, inverse (negative regression coefficient); dir, direct (positive regression coefficient).

*Significant correlations.

The individual change in oxygen consumption index resulting from a blood transfusion was significantly correlated with the pretransfusion oxygen consumption index, arteriovenous oxygen difference, mixed venous oxygen saturation, oxygen extraction ratio, and pulmonary capillary wedge pressure (Table 4). Stepwise linear regression analysis confirmed pretransfusion oxygen consumption index as the most significant independent factor determining the individual change in oxygen consumption index resulting from a blood transfusion (Table 4). Pretransfusion age and mean arterial pressure were additional independent factors found to influence the individual change in oxygen consumption index resulting from a blood transfusion, although the individual change in oxygen consumption index was not significantly correlated to these factors in simple linear regression analyses.

Interestingly, preoperative ejection fraction was significantly correlated with the pretransfusion oxygen consumption index (Fig. 2). Stepwise linear regression analysis confirmed pretransfusion oxygen consumption index as the only significant independent factor determining the individual change in oxygen consumption index resulting from a blood transfusion.
DISCUSSION

This study demonstrates that the effect of an allogeneic blood transfusion is variable in patients after cardiovascular operations and is best related to oxygen delivery and oxygen consumption variables before a blood transfusion. In contrast, the individual response is not significantly correlated with patient characteristics such as age and preoperative ejection fraction nor with the hemoglobin concentration before a blood transfusion.

One of the most important goals of a blood transfusion is to improve oxygen delivery and, consequently, oxygen metabolism. Other effects of blood transfusions, such as increases in arterial or cardiac filling pressures, can be achieved by catecholamine therapy or infusion of crystalloids and colloids, treatments that are devoid of the hazards of allogeneic blood transfusions (15, 16). The present study indicates that blood transfusions, indeed, augment oxygen delivery but do not generally enhance oxygen consumption. This is in agreement with earlier studies that consistently document an increase in oxygen delivery (2–12) but only rarely an increase in oxygen consumption (2, 4, 11, 17). An important clinical problem is that it is impossible, at present, to identify prospectively the patients who will respond to a blood transfusion with an increase in oxygen consumption in specific situations (13, 14). The present study indicates that a low oxygen consumption index was most closely related to an increase in oxygen consumption resulting from a subsequent blood transfusion (Fig. 3). Additionally, individual responses in cardiac index (Fig. 1) and oxygen delivery index (Fig. 2) were most significantly related to oxygen delivery- and oxygen consumption-related variables, such as low cardiac index, low oxygen delivery, and low oxygen consumption before a subsequent blood transfusion. Determining these oxygen delivery- and oxygen consumption-related variables, thus, allows us to better predict the individual effect of a blood transfusion regarding augmentation of oxygen delivery and oxygen consumption.

Preoperative ejection fraction and age were unrelated to the individual responses in cardiac index, oxygen delivery index, and oxygen consumption index re-
sulting from a blood transfusion (Figs. 4 and 5). Interestingly, in patients scheduled for aortocoronary bypass surgery undergoing acute normovolemic hemodilution, age and ejection fraction also did not influence the individual response during hemodilution (18); additionally, elderly patients reacted similarly to younger patients to acute normovolemic hemodilution (16, 19). Age and ejection fraction, thus, appear to be of minor importance regarding tolerance of acute anemia and response to blood transfusions, even in these relatively high-risk patients (97% ASA class IV).

The generally lacking increase in oxygen consumption after a blood transfusion may be related to the fact that oxygen consumption was not dependent on oxygen supply before a blood transfusion. This is relatively likely, given that an extreme hemodilution to a hemoglobin concentration of 3–4 g/dL is necessary to induce oxygen supply dependency in experimental animals, which is associated with a marked lactic acidosis (20, 21). Although we did not determine arterial lactate levels consistently in the present study, lactic acidosis was unlikely to be present before a blood transfusion because of a near-normal arterial pH and base excess (Table 2). Therefore, oxygen supply dependency was unlikely in the patients of the present study at a relatively high mean hemoglobin concentration of 8.1 ± 0.1 g/dL, and when oxygen delivery is augmented in the nonoxygen supply-dependent range, no increase in oxygen consumption is expected.

Storage-related alterations in red blood cells may additionally explain why oxygen consumption did not increase after a blood transfusion. In studies, Fitzgerald et al. (20) and Sielenkämper et al. (21) recently demonstrated that only fresh blood (stored ≤3 days) restored oxygen consumption in oxygen supply-dependent animals but not blood stored for 28 days. In addition, Marik and Sibbald (8) reported even a decrease in gastric intramucosal pH resulting from transfusion of blood stored in septic patients, indicating worsening rather than improvement of tissue oxygenation. The age of the blood transfused in the present study is not exactly known but is very likely >3 days. Two main reasons have

Figure 3. Individual changes in oxygen consumption index (\(\dot{V}O_2\)I) related to cardiac index before a blood transfusion (CI before; A), oxygen delivery index before a blood transfusion (\(\dot{D}O_2\)I before; B), and oxygen consumption index before a blood transfusion (\(\dot{V}O_2\)I before; C). In each graph, the linear regression equation (y = a + bx), the p value, and the coefficient of determination (R^2) are indicated. Underlined p value indicates significance after full Bonferroni correction (p < .0019).

Figure 4. Individual changes in cardiac index (CI diff; A), oxygen delivery index (\(\dot{D}O_2\)I diff; B), and oxygen consumption index (\(\dot{V}O_2\)I diff; C) related to preoperative ejection fraction (Preoperative EF). In each graph, the linear regression equation (y = a + bx), the p value, and the coefficient of determination (R^2) are indicated.

Figure 5. Individual changes in cardiac index (CI diff; A), oxygen delivery index (\(\dot{D}O_2\)I diff; B), and oxygen consumption index (\(\dot{V}O_2\)I diff; C) related to the age of the patients. In each graph, the linear regression equation (y = a + bx), the p value, and the coefficient of determination (R^2) are indicated.
been discussed as to why stored blood is unable to restore oxygen consumption, even in oxygen supply-dependent animals (20, 21). First, deformability of red blood cells decreases with storage (22), thereby impeding access to the capillary bed (20, 21) and resulting in an early entrapment in various organs (23). Second, 2,3-diphosphoglycerate concentration decreases with storage (24, 25), resulting in an increased oxygen affinity and, thereby, impeding oxygenation in the microcirculation. After transfusion, 2,3-diphosphoglycerate concentration gradually increases over 72 hrs with ~50% recovery after 3–6 hrs (25). The decrease in deformability and the decrease in 2,3-diphosphoglycerate concentration both compromise the ability of the red blood cell to oxygenate the microcirculation. However, with a transfusion duration of ~5 hrs, some recovery of 2,3-diphosphoglycerate concentration should have occurred, with a concomitant increase in oxygen consumption in an oxygen supply-dependent situation. The lack thereof again suggests a lack of oxygen supply dependency before the blood transfusion.

Several aspects of this study deserve comments. First, the study was designed as a prospective chart review of all patients with a pulmonary artery catheter, treated in the cardiovascular surgical intensive care unit between May 1, 1994, and April 30, 1995. This period was chosen because November 1, 1994, blood transfusion guidelines were altered such that the hematocrit at which a blood transfusion was advised was decreased by 5%, which enabled us to study a wide range of hemoglobin values before a transfusion. This was, indeed, achieved, with hemoglobin concentrations before a blood transfusion ranging from 5.0 to 11.8 g/dL. Second, in addition to linear regression analyses, stepwise linear regression analyses were used to determine the most important and independent factors related to an augmentation of oxygen delivery and oxygen consumption resulting from a blood transfusion. The most relevant factor found with simple linear regression analyses was always confirmed by stepwise linear regression analyses. In addition, pretransfusion mixed venous oxygen saturation and dobutamine infusion rates were found to be significant in terms of the individual change in cardiac index resulting from a blood transfusion, although the individual change in cardiac index was not significantly related to these factors in simple linear regression analyses. This can be explained by the fact that cardiac index values before and after a blood transfusion were significantly correlated with mixed venous oxygen saturation before a blood transfusion; however, the individual change in cardiac index was not correlated to the mixed venous oxygen saturation before a blood transfusion. Similarly, cardiac index before and after a blood transfusion was significantly correlated with the dobutamine infusion rate before a blood transfusion; however, the individual change in cardiac index was not correlated to the dobutamine infusion rate before a blood transfusion. The same applies for age and mean arterial pressure, which became additional significant factors in the stepwise regression analysis with regard to the individual change in oxygen consumption without being significant in simple linear regression analyses. Third, it might be regarded as a disadvantage that a small amount of colloid was infused concomitantly to the blood transfusion. However, this small amount of colloid (105 ± 9 mL) just about compensated for the concomitant blood loss in these postoperative cardiosurgical patients (146 ± 13 mL). With the blood transfusion given relatively slowly (~5 hrs), this resulted in stable cardiac filling pressures. In conjunction, this enabled us to study the effect of an increase in hemoglobin concentration devoid of concomitant alterations in preload.

Interestingly, individual changes in cardiac index, oxygen delivery, and oxygen consumption resulting from a blood transfusion were not significantly correlated with the pretransfusion hemoglobin concentration (Fig. 6). Considering the considerable range of pretransfusion hemoglobin concentrations of 5.0–11.8 g/dL and the relatively high-risk population investigated (97% ASA class IV), this represents an astonishing finding documenting the excellent anemia tolerance in these postoperative cardiosurgical patients. This finding also confirms the recommendation of the American Society of Anesthesiologists that blood transfusions should not be dictated by a single hemoglobin “trigger” but instead should be based on the patient’s risk of developing complications of inadequate oxygenation (15).

In conclusion, the present study indicates that the individual response to a blood transfusion is relatively variable in patients after cardiovascular operations and was not correlated with patient characteristics such as age and preoperative...
ejection fraction or pretransfusion hemo-
globin concentration. In contrast, the in-
dividual responses were correlated with
pretransfusion oxygen delivery and oxy-
gen consumption-related variables. In-
cluding oxygen delivery and oxygen con-
sumption, variables into transfusion
decision, thus, may enable a more indi-
vidual use of allogeneic blood in specific

REFERENCES

1. Hebert PC, Hu LQ, Biro GP: Review of phys-
   iologic mechanisms in response to anemia.
   Can Med Assoc J 1997; 156:S27–S40
dependence of oxygen consumption
on oxygen delivery in acute respiratory
failure secondary to AIDS-related Pneu-
cystis carinii pneumonia. Chest 1990; 98:
1463–1466
consumption is independent of changes in
oxygen delivery in severe adult respiratory
143:1267–1273
4. Stefes CP, Bender JS, Levison MA: Blood
transfusion and oxygen consumption in sur-
and catecholamine infusion on oxygen deliv-
ery and consumption in patients with sepsis.
6. Dietrich KA, Conrad SA, Hebert CA, et al: Carbo-
vascular and metabolic response to red
blood cell transfusion in critically ill vol-
ume-resuscitated nonsurgical patients. Crit
Care Med 1990; 18:940–944
7. Conrad SA, Dietrich KA, Hebert CA, et al: Effect of red cell transfusion on oxygen con-
sumption following fluid resuscitation in
8. Mark PE, Sibbald WJ: Effect of stored-blood
transfusion on oxygen delivery in patients
with sepsis. JAMA 1993; 269:3024–3029
fects of blood transfusion on oxygen trans-
port variables in severe sepsis. Crit Care Med
1993; 21:1312–1318
10. Mink RB, Pollack MM: Effect of blood trans-
fusion on oxygen consumption in pediatric
septic shock. Crit Care Med 1990; 18:
1087–1091
11. Lucking SE, Williams TM, Chatten FC, et al:
Dependence of oxygen consumption on oxy-
gen delivery in children with hyperdynamic
septic shock and low oxygen extraction. Crit 
Care Med 1990; 18:1316–1319
evaluation of current transfusion practices
in patients in surgical intensive care units.
13. Belisle S, Van der Linden P, Hardy JF: Cor-
rection of anaemia: The time has come to
evaluate tolerance for red cell depletion. Can
transfusion on oxygen uptake: Old concepts adapted to new therapeutic strate-
15. Task Force on Blood Component Therapy: A
report by the American Society of Anesthe-
siologists Task Force on blood component
therapy: Practice guidelines for blood com-
ponent therapy. Anesthesiology 1996; 84:
732–747
vascular and coronary physiology of acute
isoolemic hemodilution: A review of non-
oxygen-carrying and oxygen-carrying solu-
17. Shah DM, Gottlieb ME, Rahm RL, et al: Fail-
ure of red blood cell transfusion to increase
oxygen transport or mixed venous PO2 in
mobilization tolerance in patients with cor-
ony artery disease who are receiving chronic
β-adrenergic blocker therapy. Anesth Analg
1996; 82:687–694
Hemodilution tolerance in elderly patients
without known cardiac disease. Anesth Analg
1996; 82:681–686
20. Fitzgerald RD, Martin CM, Dietz GE, et al:
Transfusing red blood cells stored in citrate
phosphate dextrose adenine-1 for 28 days
fails to improve tissue oxygenation in rats.
Crit Care Med 1997; 25:726–732
21. Sielenkämper AW, Chin Yee IH, Martin CM,
et al: Diaspirin crosslinked hemoglobin im-
proves systemic oxygen uptake in oxygen
supply-dependent septic rats. Am J Respir 
Crit Care Med 1997; 156:1066–1072
formability of stored red blood cells: Rela-
tionship to degree of packing. Transfusion
1982; 22:96–101
23. Simchon S, Jan KM, Chien S: Influence of
reduced red cell deformability on regional
blood flow. Am J Physiol 1987; 253:
H898–H903
age of saline-adrenaline-glucose-mannitol-
suspended red cells in a new plastic container:
Polyvinylchloride plasticized with butyryl-n-
triethyl-citrate. Transfusion 1991; 31:26–29
25. Heaton A, Keegan T, Holme S: In vivo regen-
eration of red cell 2,3-diphosphoglycerate
following transfusion of DPG-depleted AS-1,
AS-3 and CPDA-1 red cells. Br J Haematol
1989; 71:131–136