Effect of Heart Rate Control With Esmolol on Hemodynamic and Clinical Outcomes in Patients With Septic Shock: A Randomized Clinical Trial

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IMPORTANCE β-Blocker therapy may control heart rate and attenuate the deleterious effects of β-adrenergic receptor stimulation in septic shock. However, β-Blockers are not traditionally used for this condition and may worsen cardiovascular decompensation related through negative inotropic and hypotensive effects.

OBJECTIVE To investigate the effect of the short-acting β-blocker esmolol in patients with severe septic shock.

DESIGN, SETTING, AND PATIENTS Open-label, randomized phase 2 study, conducted in a university hospital intensive care unit (ICU) between November 2010 and July 2012, involving patients in septic shock with a heart rate of 95/min or higher requiring high-dose norepinephrine to maintain a mean arterial pressure of 65 mm Hg or higher.

INTERVENTIONS We randomly assigned 77 patients to receive a continuous infusion of esmolol titrated to maintain heart rate between 80/min and 94/min for their ICU stay and 77 patients to standard treatment.

MAIN OUTCOMES AND MEASURES Our primary outcome was a reduction in heart rate below the predefined threshold of 95/min and to maintain heart rate between 80/min and 94/min by esmolol treatment over a 96-hour period. Secondary outcomes included hemodynamic and organ function measures, norepinephrine dosages at 24, 48, 72, and 96 hours; and adverse events and mortality occurring within 28 days after randomization.

RESULTS Targeted heart rates were achieved in all patients in the esmolol group compared with those in the control group. The median AUC for heart rate during the first 96 hours was −28/min (IQR, −37 to −21) for the esmolol group vs −6/min (95% CI, −14 to 0) for the control group with a mean reduction of 18/min (P < .001). For stroke volume index, the median AUC for esmolol was 4 mL/m² (IQR, −1 to 10) vs 1 mL/m² for the control group (IQR, −3 to 5; P = .02), whereas the left ventricular stroke work index for esmolol was 3 mL/m² (IQR, 0 to 8) vs 1 mL/m² for the control group (IQR, −2 to 5; P = .03). For arterial lactatemia, median AUC for esmolol was 0.1 mmol/L (IQR, −0.6 to 0.2) vs 0.1 mmol/L for the control group (IQR, −0.3 for 0.6; P = .007); for norepinephrine, −0.11 μg/kg/min (IQR, −0.46 to 0.02) for the esmolol group vs −0.01 μg/kg/min (IQR, −0.2 to 0.44) for the control group (P = .003). Fluid requirements were reduced in the esmolol group: median AUC was 3975 mL/24 h (IQR, 3663 to 4200) vs 4425 mL/24 h (IQR, 4038 to 4775) for the control group (P < .001). We found no clinically relevant differences between groups in other cardiopulmonary variables nor in rescue therapy requirements. Twenty-eight day mortality was 49.4% in the esmolol group vs 80.5% in the control group (adjusted hazard ratio, 0.39; 95% CI, 0.26 to 0.59; P < .001).

CONCLUSIONS AND RELEVANCE For patients in septic shock, open-label use of esmolol vs standard care was associated with reductions in heart rates to achieve target levels, without increased adverse events. The observed improvement in mortality and other secondary clinical outcomes warrants further investigation.

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Sepsis is associated with excessive sympathetic outflow, high plasma catecholamine levels, myocardial depression, vascular hyporeactivity, and autonomic dysfunction. Typically, patients have a low resistance, high-cardiac output circulation with tachycardia and arterial hypotension that may be poorly or even nonresponsive to exogenous catecholamine vasopressors. Although norepinephrine is the current recommended mainstay of treatment for sepsis-related hypotension, excessive adrenergic stress has multiple adverse effects including direct myocardial damage (e.g., Takotsubo [stress] cardiomyopathy and tachyarrhythmias), insulin resistance, thrombogenicity, immunosuppression, and enhanced bacterial growth. High plasma catecholamine levels, the extent and duration of catecholamine therapy, and tachycardia are all independently associated with poor outcomes in critically ill patients.

High sympathetic stress is also implicated in sepsis-induced myocardial depression. Patients with sepsis often remain tachycardic, even after excluding common causes such as hypovolemia, anemia, agitation, and drug effects. β-Adrenergic blockade may enable heart rate control and limit adverse events related to sympathetic overstimulation. In animal models of sepsis, β-blockade appears beneficial, particularly when given as pretreatment. Although heart rate control is likely to improve cardiovascular performance, concerns that β-blocker therapy in human septic shock may lead to cardiovascular decompensation must be considered. A good safety profile was reported in patients in septic shock who were given oral metoprolol to achieve heart rates of less than 95/min; however, intravenous β-blocker therapy has not been formally investigated.

We hypothesized that intravenous β-blockade titrated to achieve heart rate control in septic shock represents an effective approach to enhance myocardial function and improve outcome without increased complications. The present study aimed to determine whether the short-acting intravenous β₁-adrenoreceptor blocker, esmolol, could reduce heart rate to be lower than a predefined threshold and measured subsequent effects on systemic hemodynamics, organ function, adverse events, and 28-day mortality.

Methods

Patients

After approval by the local institutional ethics committee, we performed the study in the 18-bed multidisciplinary intensive care unit (ICU) of the University of Rome “La Sapienza” Hospital, after written informed consent from the patients’ next of kin. Enrollment occurred between November 2010 and July 2012. Inclusion criteria were the presence of septic shock requiring norepinephrine to maintain a mean arterial pressure (MAP) of 65 mm Hg or higher despite appropriate volume resuscitation (pulmonary arterial occlusion pressure ≥12 mm Hg and central venous pressure ≥8 mm Hg), and a heart rate of 95/min or higher.

Exclusion criteria were age younger than 18 years, β-blocker therapy prior to randomization, pronounced cardiac dysfunction (i.e., cardiac index ≥2.2 L/min/m² in the presence of a pulmonary arterial occlusion pressure >18 mm Hg), significant valvular heart disease, and pregnancy. All patients were sedated with sufentanil and propofol and received mechanical ventilation using a volume-controlled mode with targeted tidal volumes of 6 mL/kg or less of predicted body weight.

Hemodynamics, Global Oxygen Transport, and Acid-Base Balance

Systemic hemodynamic monitoring included pulmonary artery catheterization (7.5F catheter, Edwards Lifesciences) and a radial artery catheter. MAP, central venous, mean pulmonary arterial, and occlusion pressures were measured at end-expiration. We monitored heart rate and ST segments continuously by electrocardiography. We measured cardiac index using the continuous thermodilution technique (Vigilance II, Edwards Lifesciences). We sampled arterial and mixed-venous blood intermittently for blood gas analyses to determine oxygen tensions and saturations, carbon dioxide tensions, pH, standard bicarbonate, and base excess. Left and right ventricular stroke work, oxygen delivery, consumption indexed to body surface area, and oxygen extraction ratios were calculated using standard formulae.

We analyzed arterial blood samples for lactate, standard hematometry, biochemistry, kidney and liver function, coagulation profile tests, amylase, lipase, antithrombin, cardiac troponin I, creatine kinase MB isoenzyme (CK-MB), and C-reactive protein.

Study Design

We designed the present study as a single-center, open-label, randomized 2-group phase 2 trial. Our primary outcome was to determine whether esmolol could reduce heart rates to be lower than the predefined threshold of 95/min and to maintain heart rate between 80/min and 94/min for the duration of the patients’ ICU stay. Secondary outcomes included the effect of esmolol on norepinephrine requirements, cardiorespiratory and oxygenation indices, safety end points (including markers of organ function and injury and rescue therapy with other drugs), and 28-day overall survival.

After 24 hours of hemodynamic optimization aimed at establishing an adequate circulating blood volume (judged by pulmonary artery occlusion pressure of ≥12 mm Hg and central venous pressures of ≥8 mm Hg), a mixed venous oxygen saturation higher than 65% and a MAP of 65 mm Hg or higher, we enrolled patients if they were still requiring norepinephrine and their heart rate persisted at 95/min or higher. Patients were randomly assigned by a computer-based random-number generator to receive conventional management with or without a continuous esmolol infusion titrated to maintain heart rate between 80/min and 94/min (see eMethods in the Supplement for additional details on randomization procedures).

The esmolol infusion commenced at 25 mg × h⁻¹ and progressively increased the rate at 20-minute intervals in increments of 50 mg × h⁻¹, or more slowly at the discretion of the
investigators, to reach the predefined threshold rate within 12 hours. We continued infusing esmolol to maintain the predefined heart rate threshold until either ICU discharge or death with an upper dose limit of 2000 mg × h⁻¹. Participant study flow data are presented in Figure 1.

During the first 96 hours of the intervention period, we gave fluid challenges, as necessary, to maintain filling pressures as described above. We transfused packed red blood cells when hemoglobin concentrations decreased to less than 7 g/dL⁻¹, or if the patient exhibited clinical signs of inadequate systemic oxygen supply. We titrated norepinephrine to maintain MAP of 65 mm Hg or higher and gave all patients intravenous hydrocortisone (300 mg/d⁻¹) as a continuous infusion. If mixed venous oxygen saturation decreased to less than 65% despite appropriate arterial oxygenation (≥95%) and hemoglobin concentrations of 8 g/dL⁻¹ or higher, arterial lactate concentrations increased, or both, we administered the nonadrenergic calcium sensitizer levosimendan to improve systemic oxygen delivery at a dose of 0.2 μg/kg/min (without a loading bolus dose) for 24 hours.

We recorded all hemodynamic measurements, laboratory variables, blood gas analyses, and norepinephrine requirements at baseline and at 24, 48, 72, and 96 hours after randomization. We also recorded adverse events, including death from any cause, occurring during the 28 days following randomization.

Sample Size Calculation
To detect a 20% change in heart rate (estimated standard deviation 40%) with a power of 80% and a type I error rate of .05, by using a 2-sided t test, we calculated that 64 patients per group would be required. Because data distribution was unknown a priori and data were analyzed by nonparametric analysis, we assumed a worst-case scenario with a minimal asymptotic relative efficiency of 0.864 for the Wilcoxon-Mann-Whitney test, resulting in a minimum required sample size of 75 patients per group.³³

Statistical Analysis
We used SPSS version 20 (IBM Corp) for statistical analysis. Continuous data are summarized by median (interquartile range [IQR]), if not otherwise specified. We performed all analyses according to the intention-to-treat principle. We compared baseline and demographic data using the Wilcoxon-Mann-Whitney or χ² test, as appropriate. To avoid multiple comparisons, we calculated areas under the curve (AUCs) relative to baseline values for continuous variables with repeated measurements, as suggested by Matthews et al²⁹ (see eMethods in the Supplement for details). We then compared AUCs between the 2 treatment groups with the Wilcoxon-Mann-Whitney test. Binary 28-day mortality of the 2 groups was compared by a χ² test. In addition, we compared 28-day overall survival by means of a log-rank test and by fitting a multivariable Cox regression model. We built this latter model by using stepwise forward inclusion based on likelihood ratio P values for which study group assignment, sex, multidrug-resistant Actinobacter or Klebsiella infection, and levosimendan infusion were considered as cofactors, and age, body mass index (BMI, calculated as weight in kilograms divided by height in meters squared), Simplified Acute Physiology Score (SAPS) II, baseline values of norepinephrine dosage, arterial lactate concentration, and platelet count were considered as covariates.¹⁵,¹⁶ Survival plots for time-to-event outcomes were designed as recommended by Pocock et al.⁷ We initially estimated mortality risk from the SAPS II score.¹⁸ This is usually computed using the most extreme values collected over the first 24 hours following ICU admission, whereas we used values measured at study entry, by which time patient stabilization has usually generated a lower SAPS II score and thus underestimates mortality risk. Patients requiring high-dose norepinephrine, a requirement in our study, have a very high mortality.¹⁹,²⁰ The primary end point was confirmatory tested at a 2-sided significance level of α = .05. All other given P values are exploratory. Additional and alternative statistical approaches are detailed in the eMethods in the Supplement.

Results

Patients
After hemodynamic optimization, we screened 336 patients with 176 being excluded due to heart rate values of less than 95/min (n = 166) or previous β-blocker therapy (n = 10). In another 6 patients, we could not obtain informed consent. Thus, a total of 154 patients were included and randomly assigned to the 2 study groups in a 1:1 ratio (Figure 1).

Data on the primary end point were complete, whereas only 29 of 770 data sets (154 patients × 5 time points) had at least 1 laboratory variable missing (eg, troponin). To account for these missing data, calculation of AUC was based on the assumption that the missing value represents the mean of the values before and after.

Demographic Data
Baseline data were similar among study groups with respect to age, sex, BMI, comorbidities, SAPS II score, focus of sepsis,
pathogen spectrum, norepinephrine dose, and first 24-hour fluid input (Table 1). The high SAPS II score and the high norepinephrine requirement at study entry (Table 1) are indicative of patients who are at high risk of mortality.17-19

Hemodynamic Variables and Other Therapies

The target range for heart rate was 80/min to 94/min in all patients in the esmolol group, which was significantly lower throughout the intervention period than what was achieved in the control group. The median AUC over the first 96 hours was −28/min (IQR, −37 to −21) for the esmolol group vs −6/min (−14 to 0) for the control group (P < .001; Figure 3). MAP was maintained despite a marked reduction in norepinephrine requirements in the esmolol group with a median AUC of −0.11 μg/kg/min (IQR, −0.46 to 0) vs −0.01 μg/kg/min (−0.2 to 0.44) in the control group (P = .003; Figure 3). Stroke volume, systemic vascular resistance, and left ventricular stroke work indices were increased in the esmolol group (Figure 3, Table 2). Although reductions in systemic oxygen delivery were greater in the esmolol group with a median AUC of −100 mL/min/m² (IQR, −211 to −38) vs −32 mL/min/m² (IQR, −108 to 21) in the control group (P < .001) and had reduced consumption with a median AUC of −29 mL/min/m² (IQR, −55 to 0) in the esmolol group vs −4 mL/min/m² (IQR, −29 to 20) in the control group (P < .001; eTable 1 in the Supplement), the need for levo- mendan rescue therapy did not differ between groups (49.4% of esmolol patients vs 40.3% control patients; P = .39). Fluid requirements were reduced in the esmolol group with a median AUC of 3975 mL/24 h (IQR, 3663 to 4200) vs 4425 mL/24 h (IQR, 4038 to 4775) in the control group (P < .001; Table 2). We could find no clinically relevant difference between treatment groups for any other systemic or pulmonary hemodynamic variable.

Acid-Base and Metabolic Variables

The median AUCs were higher for arterial pH for the esmolol group: 0.28 units (IQR, −0.01 to 0.08) vs −0.02 units (IQR, −0.06 to 0.06) for the control group (P = .003) and for base excess, 0.8 mmol/L (−1.2 to 3.6) for the esmolol group vs −0.5 mmol/L (IQR, −2.1 to 2.8) for the control group (P = .03), whereas the median AUC for arterial lactate concentration was lower for the esmolol group at −0.1 mmol/L (IQR −0.6 to 0.3) than for the control group at 0.1 mmol/L (IQR, −0.3 to 0.6; P = .006). Partial gas pressures and oxygen saturations did not differ between groups (eTable 1 in the Supplement).

Markers of Organ Function and Injury

Kidney function, assessed by the Modification of Diet in Renal Disease formula for estimating glomerular filtration rate, was better maintained in the esmolol group: median AUC of 14 mL/min/1.73 m² (IQR, 4 to 37) than in the control group vs 2 mL/min/1.73 m² (IQR, −7 to 20; P < .001). The trend remained when excluding patients receiving renal replacement therapy with a median AUC in the esmolol group of 10 mL/min/1.73 m² (IQR, 1 to 35) vs −2 mL/min/1.73 m² (IQR, −9 to 4) in the control group (P < .001; Figure 4). During ICU stay, the percentage of patients requiring renal replacement therapy did not differ between groups: 40.3% in the esmolol group vs 41.6% in the control group. The arterial oxygen partial pressure to inspired oxygen fraction ratio was higher in the esmolol group with a median AUC of 38 mm Hg (IQR, −22 to 72) than in the control group 6 mm Hg (IQR, −46 to 59; P = .03). Liver function tests did not differ between groups, whereas markers of myocardial injury were lower in the esmolol group with the median AUC for troponin T in the esmolol group being −0.01 (IQR, −0.05 to 0.00) vs 0.00 (IQR, −0.01 to 0.02) for the control group (P = .002) and the CK-MB for the esmolol group was −1 (IQR, −4 to 0) vs control 0 (IQR, −1 to 1) for the control group (P = .02; eTable 2 in the Supplement).

### Table 1. Baseline Characteristics of the Study Patients

<table>
<thead>
<tr>
<th></th>
<th>Esmolol (n = 77)</th>
<th>Control (n = 77)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age, median (IQR), y</strong></td>
<td>66 (52–75)</td>
<td>69 (58–78)</td>
</tr>
<tr>
<td><strong>Men, No. (%)</strong></td>
<td>54 (70)</td>
<td>53 (69)</td>
</tr>
<tr>
<td><strong>Body mass index, median (IQR)</strong></td>
<td>29 (26–33)</td>
<td>28 (25–32)</td>
</tr>
<tr>
<td><strong>SAPS II score, median (IQR)</strong></td>
<td>52 (47–60)</td>
<td>57 (49–62)</td>
</tr>
<tr>
<td><strong>Norepinephrine dosage, median (IQR), μg/kg/min</strong></td>
<td>0.38 (0.21–0.87)</td>
<td>0.40 (0.18–0.71)</td>
</tr>
<tr>
<td><strong>Arterial lactate, median (IQR), μg/kg/min</strong></td>
<td>1.5 (1.1–2.7)</td>
<td>1.9 (1.1–3.1)</td>
</tr>
<tr>
<td><strong>Platelet count, median (IQR), × 10^10/μL</strong></td>
<td>178 (126–272)</td>
<td>129 (73–206)</td>
</tr>
<tr>
<td><strong>Fluid input, mL, 24 h prior to inclusion, median (IQR)</strong></td>
<td>4700 (4300–5200)</td>
<td>4800 (4100–5325)</td>
</tr>
<tr>
<td><strong>Causes of septic shock, No.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Necrotizing fasciitis</strong></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Pyelonephritis</strong></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Peritonitis</strong></td>
<td>21</td>
<td>30</td>
</tr>
<tr>
<td><strong>Pneumonia</strong></td>
<td>54</td>
<td>44</td>
</tr>
<tr>
<td><strong>Pathogens, No. (%)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Klebsiella spp</strong></td>
<td>29 (38.0)</td>
<td>20 (26.0)</td>
</tr>
<tr>
<td><strong>Acinetobacter spp</strong></td>
<td>6 (7.8)</td>
<td>6 (7.8)</td>
</tr>
<tr>
<td><strong>Acinetobacter spp + Klebsiella spp</strong></td>
<td>11 (14.3)</td>
<td>8 (10.4)</td>
</tr>
<tr>
<td><strong>Staphylococcus aureus</strong></td>
<td>6 (7.8)</td>
<td>6 (7.8)</td>
</tr>
<tr>
<td><strong>Escherichia coli</strong></td>
<td>3 (3.9)</td>
<td>8 (10.4)</td>
</tr>
<tr>
<td><strong>Pseudomonas spp</strong></td>
<td>5 (6.5)</td>
<td>4 (5.2)</td>
</tr>
<tr>
<td><strong>Aspergillus spp</strong></td>
<td>0 (0.0)</td>
<td>3 (3.9)</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td>17 (22.0)</td>
<td>22 (28.6)</td>
</tr>
<tr>
<td><strong>Preexisting conditions, No. (%)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Coronary artery disease</strong></td>
<td>25 (32.5)</td>
<td>21 (27.3)</td>
</tr>
<tr>
<td><strong>Congestive heart failure</strong></td>
<td>11 (14.3)</td>
<td>13 (16.9)</td>
</tr>
<tr>
<td><strong>Chronic kidney disease</strong></td>
<td>5 (6.5)</td>
<td>4 (5.2)</td>
</tr>
<tr>
<td><strong>Chronic obstructive pulmonary disease</strong></td>
<td>16 (20.8)</td>
<td>20 (26.0)</td>
</tr>
</tbody>
</table>

**Abbreviation:** IQR, interquartile range.

*Calculated as weight in kilograms divided by height in meters squared

1 The Simplified Acute Physiology Score (SAPS) II is calculated from a point score of 12 routinely measured physiological and biochemical variables within the first 24 hours of intensive care unit admission. The range varies from 0 to 163 points with more extreme values scoring more points.18

### Study Drug Dosage

The median esmolol dosage was 100 mg/h (IQR, 50–300) without relevant trends over time (Figure 2). We did not exceed the maximum permitted dosage of 2000 mg/h.
Outcome Data
The esmolol group had a 28-day mortality rate of 49.4% vs 80.5% in the control group ($P < .001$). Overall survival was higher in the esmolol group (Figure 5). Multivariable Cox regression analysis revealed that esmolol group allocation (hazard ratio [HR], 0.392; 95% CI, 0.261-0.590; $P < .001$) and SAPS Figure 2. Esmolol and Norepinephrine Drug Infusions in Study Patients

A

Esmolol dosage

B

Norepinephrine dosage

No. of patients
Control
Esmolol
No. of patients
Control
Esmolol

Figure 3. Changes in Hemodynamic Variables

Heart rate

Mean arterial pressure

Stroke volume index

Cardiac index

No. of patients
Control
Esmolol
No. of patients
Control
Esmolol

Solid lines represent median values. The shaded areas bordered by dotted lines represent the upper and lower quartiles by colors.

Solid lines represent median values. The shaded areas bordered by dotted lines represent the upper and lower quartiles. MAP indicates mean arterial pressure.
II score (HR, 1.033; 1.013–1.054; \( P < .001 \)) were the only variables to be included in the model for optimal prediction of overall survival (eAppendix in the Supplement). However, the esmolol dose did not influence 28-day mortality (odds ratio [OR], 1.000; 95% CI, 0.999–1.001; Table 3).

### Discussion

In a cohort of patients with septic shock and high risk of mortality, our open-label use of esmolol after initial hemodynamic optimization resulted in maintenance of heart rate within the target range of 80/min to 94/min. Compared with standard treatment, esmolol also increased stroke volume, maintained MAP, and reduced norepinephrine requirements without increasing the need of inotropic support or causing adverse effects on organ function. There was an associated improvement in 28-day survival.

Tachycardia increases cardiac workload and myocardial oxygen consumption. In addition, shortening of diastolic relaxation time and impairment of diastolic function further...
affect coronary perfusion, contributing to a lower ischemic threshold. Excessive sympathetic activation also leads to catecholamine-induced cardiomyocyte toxic effects characterized by inflammation, oxidative stress, and abnormal calcium handling resulting in left ventricular dilatation, apical ballooning, myocardial stunning, apoptosis, and necrosis. Taken together, these mechanisms contribute to worsening of septic myocardial dysfunction and increased mortality.

Tachycardia in septic shock is controversial. The right timeframe for intervention and the optimal heart rate threshold are currently undefined. In the early unresuscitated phase of septic shock, tachycardia represents the main mechanism to compensate for any decrease in cardiac output. In this case, heart rate reduction may derail this adaptive physiologic response, leading to a decrease in oxygen delivery that may compromise organ perfusion and function. Adequate volume resuscitation will often result in a concomitant decrease in heart rate yet, in some septic patients, tachycardia persists despite excluding other causes such as pain and agitation. Tachycardia may in such cases represent an expression of sympathetic overstimulation, in part due to activation of peripheral afferent fibers by ischemia and inflammation in peripheral tissues.

Although reducing heart rate will decrease myocardial oxygen consumption and will improve diastolic function and coronary perfusion, for patients with sepsis, an inadequate chronotropic response may potentially negatively affect cardiac output and tissue perfusion. Predefining a threshold value for heart rate is difficult because it must be individualized in the context of the patient’s overall hemodynamic status and any preexisting comorbidities. In our study, we hypothesized that a heart rate range between 80/min to 94/min was a sufficient compromise between improving cardiac performance and preserving systemic hemodynamics. We found no obvious safety issues related to the use of esmolol, a finding reflected in an open-label study of oral metoprolol given to patients with septic shock who had myocardial depression for which heart rate control (targeted at 65/min-95/min) was successfully achieved.

Table 3. Outcome Data of Study Patients

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Esmolol (n = 77)</th>
<th>Control (n = 77)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mortality</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28 d</td>
<td>38 (49.4)</td>
<td>62 (80.5)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>ICU</td>
<td>44 (57.1)</td>
<td>68 (88.3)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Hospital</td>
<td>52 (67.5)</td>
<td>70 (90.9)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Length of ICU stay, d</td>
<td>19 (11-27)</td>
<td>14 (7-25)</td>
<td>.03</td>
</tr>
<tr>
<td>Survivors', median (IQR)</td>
<td>17 (9-28)</td>
<td>21 (11-34)</td>
<td>.70</td>
</tr>
<tr>
<td>Cause of death, No./total, (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiple organ failure</td>
<td>15/52 (28.8)</td>
<td>26/70 (37.1)</td>
<td></td>
</tr>
<tr>
<td>Refractory hypotension</td>
<td>32/52 (61.6)</td>
<td>44/70 (62.9)</td>
<td>.71</td>
</tr>
<tr>
<td>Unknown cause</td>
<td>5/52 (9.6%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: ICU, intensive care unit; IQR, interquartile range.

Figure 5. Survival Analysis of Study Patients

A, unadjusted survival plots (Kaplan-Meier) of patients. B, multivariable adjusted survival (Cox) at mean values of Simplified Acute Physiology Score II. Ordinate axis is scaled as “1-survival” to depict the 0 intersection without breaking the axis.

Univariate survival analysis

Adjusted survival at mean value of covariates
in 97.5% of patients within a mean 12 (SD, 12) hours. This simplifies titration against a predefined heart rate target and enables rapid resolution of any potential adverse effect after drug discontinuation. Targeted heart rates between 80/min to 94/min were achieved safely within the first 24 hours of treatment. Importantly, the norepinephrine-sparing effect was not associated with a higher need for inotropic support but rather by an increase in left ventricular stroke work. These findings suggest that lowering of heart rate by esmolol allows better ventricular filling during diastole, hence, improving stroke volume and thereby improving the efficiency of myocardial work and oxygen consumption. Together with an amelioration in catecholamine-induced toxicity, myocardial performance may be preserved during septic shock thereby facilitating survival. Administration of esmolol improved markers of tissue perfusion and organ injury, with no obvious compromise of organ function.

Adverse effects of catecholamines may become manifest over the whole course of a patient’s illness, affecting organs other than the heart. Examples include lung (pulmonary edema, pulmonary hypertension), gastrointestinal tract (inhibition of peristalsis, bowel ischemia), coagulation system (hypercoagulability, thrombus formation), immune system (inhibition of peristalsis, bowel ischemia), coagulation system (hyperglycemia and impaired glucose tolerance, muscle catabolism, increased lipolysis, and hyperlactatemia). Because noncardiac actions of β-blocker therapy may also prove beneficial, we chose to continue esmolol therapy with maintenance of the heart rate target range throughout the patient’s ICU stay.

Study limitations include selection of an arbitrary predefined heart rate threshold rather than an individualized approach titrated to specific myocardial characteristics or other biomarkers. We adopted a heart rate threshold of less than 95/min because values persisting above this level are associated with adverse cardiac events in ICU patients. Second, the study had to be nonblinded because titration of esmolol to achieve heart rate control was the primary objective. Inactive placebo would be ineffective in lowering heart rate (unless covert hypovolemia was present) and large volumes of fluid attempting to achieve this goal may prove deleterious. Third, enrollment was performed in an environment of high-endemic rates of multidrug-resistant Klebsiella and Acinetobacter baumannii strains that may have led to secondary complications. Multivariable analysis was performed to account for this infectious burden and other potential confounders. Fourth, we cannot conclude to what extent noncardiac mechanisms of esmolol contributed to the observed improvement in mortality nor conclude whether it was simply the reduction in heart rate alone. An ongoing study of heart rate control in critically ill patients using the funny channel current inhibitor, ivabradine will help to address this point.

Fifth, although mortality was not a primary end point, the unexpectedly large intergroup difference does not exclude the possibility of a chance finding or a contribution from unknown confounding factors. We did investigate a population in severe septic shock with sustained tachycardia and requiring high-dose norepinephrine, all of which are indicative of a very poor prognosis. This high-risk subset would likely gain the greatest benefit from heart rate control by β-blockade. Whether similar benefits are achieved in less sick patients requires further investigation. Appropriately powered, randomized, controlled multicenter trials are required to confirm our findings.

Conclusion

For patients in septic shock, the open-label use of esmolol was able to achieve reductions in heart rate to target levels, without an increase in adverse outcomes compared with standard treatment. Further investigation of the effects of esmolol on clinical outcomes is warranted.
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