Dynamic arterial elastance during experimental endotoxic septic shock

**CURRENT STATUS:** POSTED

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10.21203/rs.3.rs-26370/v1

**SUBJECT AREAS**

Critical Care & Emergency Medicine

**KEYWORDS**

cardiac output, arterial pressure, sepsis, septic shock, dynamic arterial elastance, stroke volume variation, pulse pressure variation
Abstract

Background: Dynamic arterial elastance (Ea dyn), the ratio between pulse pressure variation (PPV) and stroke volume variation (SVV), has been suggested as a functional parameter that is a surrogate of arterial load. We aimed to determine the effects of endotoxic septic shock and hemodynamic resuscitation on Ea dyn.

Results: Experimental randomized study in a university animal research laboratory with 18 New Zealand rabbits. Animals received placebo (SHAM, n=6) or intravenous lipopolysaccharide (LPS, Escherichia coli serotype 055:B5, 1 mg·kg⁻¹) with or without (EDX-R, n=6; EDX-NR, n=6) hemodynamic resuscitation (fluid bolus of 20 ml·kg⁻¹ and norepinephrine for restoring mean arterial pressure). Continuous arterial pressure and aortic blood flow measurements were obtained simultaneously. Cardiovascular efficiency was evaluated by the oscillatory power fraction (%Osc: oscillatory work / left ventricular (LV) total work) and the energy efficiency ratio (EER = LV total work/cardiac output). The LPS-induced endotoxic shock produced a hyperdynamic shock with high cardiac output and arterial hypotension. Ea dyn increased in septic animals (from 0.73 to 1.70; p=0.012) and dropped after hemodynamic resuscitation. Ea dyn was related with the %Osc and EER [estimates: -0.101 (-0.137 – -0.064) and -9.494 (-11.964 – -7.024); p<0.001, respectively]. So, the higher the Ea dyn, the better the cardiovascular efficiency (lower %Osc and EER).

Conclusions: In this experimental model, Ea dyn increased during endotoxic septic shock and decreased with hemodynamic resuscitation. Sepsis resulted in a reduced oscillatory power fraction and lowered EER, reflecting a better cardiovascular efficiency that was tracked by Ea dyn. Ea dyn could be a potential index of cardiovascular efficiency during septic shock.

Background

Variations in left ventricular (LV) stroke volume (SV) and arterial pulse pressure (PP) are closely related to changes in intrathoracic pressure during respiration [1]. The magnitude of these changes has been used to define preload-dependency [2]. Since the change in arterial PP for a change in SV has the dimension of elastance, the ratio between the PP variation (PPV) and SV variation (SVV) has been described as dynamic arterial elastance (Ea dyn). This parameter has been proposed as a
functional measure of the arterial load [3]. It arises from the simultaneous assessment of PP and SV changes during a respiratory cycle and is related to the cardiac modulation of volume as a function of pressure [3]. Although $E_{a_{\text{dyn}}}$ was initially defined as a variable describing central arterial tone, we have shown in an experimental rabbit model that $E_{a_{\text{dyn}}}$ is affected not only by arterial factors but also by the heart rate (HR) and the pattern of blood flow during experimental changes in arterial load conditions [4]. Moreover, we have recently demonstrated a significant relationship between $E_{a_{\text{dyn}}}$, ventriculo-arterial coupling, and LV mechanical efficiency [5]. Accordingly, $E_{a_{\text{dyn}}}$ could be considered as a composite index reflecting the interaction between both arterial and cardiac factors and potentially providing valuable information regarding cardiovascular performance and ventriculo-arterial coupling.

Although the primary function of the cardiovascular system is to deliver hydraulic energy (expressed in terms of blood flow and arterial pressure) to sustain normal physiological functions, there is an optimal combination of cardiac function and arterial system status that provides the maximum efficiency in transferring this mechanical energy from the LV to the arterial tree [6]. Prior studies have demonstrated that this ideal combination occurs when the ventricle and the arterial tree are optimally coupled [7, 8].

Septic shock has a profound impact on macrohemodynamics and also the microcirculation [9, 10]. Macrocirculatory derangements in septic shock have been characterized by a combination of a variable degree of cardiac dysfunction and a profound vasoplegia [11]. These alterations are usually the expression of a ventricular-arterial uncoupling associated with a sepsis-induced cardiovascular inefficiency [9, 12]. Moreover, septic shock has also been associated with early and sustained microcirculatory derangements that may evolve independently of macrohemodynamics [13].

Since $E_{a_{\text{dyn}}}$ has been shown to be affected by both arterial and cardiac factors, we hypothesized that sepsis-induced hemodynamic cardiovascular dysfunction could affect $E_{a_{\text{dyn}}}$. We, therefore, aimed to determine the effects of endotoxic septic shock on $E_{a_{\text{dyn}}}$, and the impact of hemodynamic resuscitation.
Methods

Eighteen New-Zealand rabbits (weight 2.5 ± 0.1 kg), supplied by the Reproduction Laboratory of the University of Cadiz, were maintained at a controlled temperature (23°C) in individual cages on a 12-h light/dark cycle with free access to food and water up to the time of experimental procedures. Animals were allowed to acclimatize to the laboratory for one week before the beginning of the experiments. All methods and protocols in this investigation were reviewed and approved (project 06-04-15-230) by the Ethical Committee for Animal Experimentation of the School of Medicine of the University of Cadiz (license 07-9604) and the Dirección General de la Producción Agrícola y Ganadera of the Junta de Andalucía. Animal care and use procedures conformed to national and European Union regulations and guidelines (Spanish Royal Decree 53/2013 and EU Directive 2010/63/EU).

Anesthesia and instrumentation. Animals were premedicated with an intramuscular dose of xylazine (10 mg·kg$^{-1}$) and ketamine (40 mg·kg$^{-1}$). Then they were tracheotomized and their lungs mechanically ventilated in volume-controlled mode (Servo 900c, Siemens-Elema, Solna, Sweden), with 8 ml·kg$^{-1}$ of tidal volume, positive end-expiratory pressure of 0 cmH$_2$O, an inspiration to expiration ratio of 1:2, inspired oxygen fraction of 0.6, and a respiratory rate of 35-40 breaths·min$^{-1}$ adjusted to maintain an end-tidal CO$_2$ between 35–45 mmHg. The right internal jugular vein was catheterized for continuous sedation with ketamine (10–40 mg·kg$^{-1}$·h$^{-1}$) and midazolam (1–3 mg·kg$^{-1}$·h$^{-1}$). The muscular blockade was maintained with a rocuronium bromide infusion (0.6–1.2 mg·kg$^{-1}$·h$^{-1}$)[14]. Adequacy of anesthesia before neuromuscular blockade and through the experiment was evaluated by the absence of any significant blood pressure and/or heart rate change in response to an external noxious stimulus. A Ringers lactate solution (6 ml·kg$^{-1}$·h$^{-1}$) was administered as a maintenance fluid therapy. Temperature was continuously monitored by a rectal probe and maintained between 38–40º using a heating pad. A 22G sterile polyethylene catheter was introduced into the right femoral artery and connected to a pressure transducer (TruWave, Edwards Lifesciences LLC, Irvine, CA, USA). This was zeroed against atmospheric pressure, and optimal damping of the arterial waveform was checked by a square wave test. The left femoral vein was used to administer
vasoactive drugs and fluid bolus.

**Hemodynamic monitoring.** A pediatric esophageal Doppler probe (KDP72; CardioQ Combi, Deltex Medical, Chichester, UK) was introduced into the esophagus until the best outline and maximal peak velocity of aortic blood waveform was obtained. Cardiac output (CO) was calculated using the minute distance of aortic blood flow, which represents the distance traveled by a column of blood in 1 min and is calculated by the Doppler system as the product of HR and the velocity-time integral of the aortic flow waveform. The arterial pressure signal was transferred from the multi-parametric monitor (S/5, Datex-Ohmeda, Helsinki, Finland) to the Doppler system and automatically synchronized with the aortic blood flow waveform for pressure-flow analysis.

**Evaluation of arterial load.** A 3-element Windkessel model was used for characterizing the arterial system[15], consisting of systemic vascular resistance [SVR=mean arterial pressure (MAP) / CO]; arterial compliance (C<sub>art</sub> = stroke volume / arterial pulse pressure)[16] and characteristic impedance (Zc). Zc represents the arterial input impedance in the absence of arterial wave reflections[17]. Assuming that arterial reflections are negligible during early systole[17, 18], Zc was estimated as the slope of the early ejection pressure-flow relationship, using the ratio between the maximum of the first derivate of pressure and flow averaged during one minute [19, 20].

The effective arterial elastance (Ea) was used as a lumped parameter of arterial load accounting for both mean and pulsatile components[21]:

[Please see the supplementary files section to view the equation.]

Where R<sub>T</sub> is the total mean vascular resistance (SVR + Zc), t<sub>s</sub> and t<sub>d</sub> are systolic and diastolic periods, respectively, and τ the diastolic time constant (τ = SVR × C<sub>art</sub>) [21].

**PPV, SVV, and dynamic arterial elastance.** PPV was calculated as the percentage changes in arterial pulse pressure during a ventilatory cycle as [(PPmax – PPmin) / (PPmax + PPmin) /2] × 100, where PPmax and PPmin represent the maximal and minimal arterial pulse pressure, respectively. The calculation of SVV was performed similarly. SVmax and SVmin were calculated by integrating the systolic component of aortic blood flow waveform, whereas PPV was derived from the femoral arterial
pressure waveform. PPV and SVV values were simultaneously analyzed and averaged during 1-min using a custom Excel macro (Microsoft Corporation, Redmond, WA, USA) (Figure 1). $E_{a\text{dyn}}$ was calculated as PPV/SVV [22].

**Left ventricular energetics.** Left ventricular energetics were analyzed from the instantaneous pressure and flow recordings. Aortic blood flow and femoral arterial pressure waveforms were recorded simultaneously during at least 20 seconds at 180 Hz and ensemble-averaged, foot-to-foot aligned using the maximum of the second derivative, and interpolated to the duration of the cardiac cycle to provide a representative waveform for analysis. An illustrative example of the signal processing is shown in Figure 2. The contribution of kinetic energy was considered negligible and not included in the analysis[18].

The left ventricular (LV) total power ($\dot{W}_{\text{tot}}$) transferred to the systemic circulation was calculated as the time-averaged integral of the instantaneous product of blood pressure ($P$) by flow ($Q$) during the whole cardiac period ($T$):

$$\dot{W}_{\text{tot}} = \frac{1}{T} \int_{0}^{T} P(t)Q(t) \, dt$$

[Please see the supplementary files section to view the equation.]

The product of mean pressure by mean flow, or steady power ($\dot{W}_{\text{std}}$), corresponds to the energy maintaining forward blood flow and represents the fraction of $\dot{W}_{\text{tot}}$ useful for organ perfusion [18, 23, 24].

[Please see the supplementary files section to view the equation.]

The oscillatory power ($\dot{W}_{\text{osc}}$) refers to the energy lost in pulsatile phenomena due to cardiac contractions:

[Please see the supplementary files section to view the equation.]

**Cardiovascular efficiency.** The oscillatory power fraction (%Osc) represents the portion of $\dot{W}_{\text{tot}}$ wasted in oscillatory power and quantifies the efficiency with which the external mechanical power was transferred into useful work from the LV to the arterial system [23-25]. Therefore, the lower the %Osc, the more efficiently LV external work is delivered to the arterial system and converted into useful work for creating blood flow. %Osc has been used as a measure of the optimization of ventriculo-
arterial coupling[23, 24].

[Please see the supplementary files section to view the equation.]

We also calculated the LV power necessary for generating one unit cardiac output for a given arterial load, as the energy efficiency ratio (EER) [25, 26]:

[Please see the supplementary files section to view the equation.]

Therefore, the lower the EER, the lower the energy required for generating blood flow for a given LV afterload.

*Tissue O$_2$ saturation.* Tissue oxygen saturation (StO$_2$) was used as a surrogate for microcirculatory perfusion. StO$_2$ was continuously assessed by using near-infrared spectroscopy (NIRS) with the INVOS 5100C monitor (Covidien, Boulder, CO, USA), as previously described[27]. A neonatal self-adhesive sensor was placed over a shaved and cleaned skin of the lateral area of the hind leg (*biceps femoris* muscle), contralateral to the femoral venous access. The sensor was held on place with adhesive tape and covered with an opaque wrapper to avoid ambient light interference. Measurements were obtained every 4 secs, and 1-min averaged for analysis.

We also considered the ratio between LV mechanical work and StO$_2$ as a measure of the work required for the cardiovascular system for given tissue perfusion, which represents an index of the performance of the coupling between the central hemodynamics and the microcirculation.

[Please see the supplementary files section to view the equation.]

So, the lower the Mmi, the lower the LV mechanical work required for sustaining tissue perfusion.

*Experimental protocol.* After completion of the surgical procedures, animals were allowed to stabilize MAP and HR (variation <5%) at least for 10 minutes. After that, they were assigned using a computer-generated random sequence to three groups (6 animals each): a sham-operated group (SHAM), a septic group (EDX), and a septic group with hemodynamic resuscitation (EDX-R). In septic animals, a purified lipopolysaccharide (LPS) prepared from *Escherichia coli* serotype 055:B5 (Sigma Chemical, St. Louis, MO) was intravenously infused over 10 mins through the femoral vein (1 mg·kg$^{-1}$ diluted in normal saline for a total volume of 8 ml, and flushed by 2 ml of normal saline to ensure a complete
delivery). The dose and rate of LPS administration were previously established on a pilot experiment with 8 animals, in which the dose was varied from 1 to 2 mg·kg⁻¹. SHAM animals received an equivalent amount of normal saline. Three hours after LPS infusion, animals in the EDX-R group received a fluid bolus of 20 ml·kg⁻¹ for 10 min. A norepinephrine infusion started at 0.25 mcg·kg⁻¹·min⁻¹ was started after fluid administration if MAP was below the baseline level. Norepinephrine was increased by 0.10 mcg·kg⁻¹·min⁻¹ every 3 mins until reaching a MAP value similar to the baseline level (±5% deviation). Hemodynamic measurements, aortic blood flow, and arterial pressure waveforms were recorded at least during 1 min at baseline and every hour up to 4 hours after LPS or placebo administration. In EDX-R animals, measurements after fluid bolus (post-infusion) and norepinephrine infusion (which corresponds to 4 hours after LPS infusion) were also obtained. After completion of the study protocol, animals were euthanized using a lethal dose of intravenous potassium chloride under deep anesthesia. Animal death was confirmed by verification of the absence of blood flow and arterial pressure tracings.

Statistical analysis. Data are expressed as the mean ± standard deviation or median (25th to 75th interquartile). The normality of data was checked by the Shapiro Wilk test. Differences between groups at baseline were performed using a one-way analysis of variance (ANOVA), and differences over time were assessed by two-way mixed ANOVA for repeated measurements. The Greenhouse-Geisser correction was used when the Mauchly test detected violation of sphericity. Whenever a significant interaction was found, pairwise comparison between groups was performed using a one-way ANOVA with the Tukey-Kramer test. Mixed-effect regression analyses were used to evaluate the impact of sepsis on the relationship between $E_{a_{dyn}}$ (the dependent variable) and arterial load ($E_a$, and its determinants: SVR, $C$, and $Z_c$), cardiac function variables (heart rate and maximal acceleration of aortic blood flow, as an index LV performance[28]); cardiac energetics ($W_{tot}$ and its components: $W_{std}$ and $W_{osc}$) and variables of cardiovascular efficiency ($\%Osc$ and EER). The effects of sepsis on $E_{a_{dyn}}$ were evaluated in the EDX group and on animals in the EDX-R group before the hemodynamic resuscitation. Models were constructed using individual animals and experimental groups as subjects.
for random factors, and experimental stages as repeated measurements with a heterogeneous first-order autoregressive covariance structure. Model selection based on the corrected Akaike’s Information Criteria, in which lower scores indicate superior fit [29]. Model parameters were estimated via the restricted maximum likelihood method, and the estimated fixed effect of each parameter quantified by using estimated value and standard error (SE). A P value < 0.05 was considered statistically significant. All statistical analyses were two-tailed and performed using MedCalc Statistical Software version 19.1 (MedCalc Software bvba, Ostend, Belgium; https://www.medcalc.org; 2016).

Results

Variations in left ventricular (LV) stroke volume (SV) and arterial pulse pressure (PP) are closely related to changes in intrathoracic pressure during respiration [1]. The magnitude of these changes has been used to define preload-dependency [2]. Since the change in arterial PP for a change in SV has the dimension of elastance, the ratio between the PP variation (PPV) and SV variation (SVV) has been described as dynamic arterial elastance (Ea\text{dy}n). This parameter has been proposed as a functional measure of the arterial load [3]. It arises from the simultaneous assessment of PP and SV changes during a respiratory cycle and is related to the cardiac modulation of volume as a function of pressure [3]. Although Ea\text{dy}n was initially defined as a variable describing central arterial tone, we have shown in an experimental rabbit model that Ea\text{dy}n is affected not only by arterial factors but also by the heart rate (HR) and the pattern of blood flow during experimental changes in arterial load conditions [4]. Moreover, we have recently demonstrated a significant relationship between Ea\text{dy}n, ventriculo-arterial coupling, and LV mechanical efficiency[5]. Accordingly, Ea\text{dy}n could be considered as a composite index reflecting the interaction between both arterial and cardiac factors and potentially providing valuable information regarding cardiovascular performance and ventriculo-arterial coupling.

Although the primary function of the cardiovascular system is to deliver hydraulic energy (expressed in terms of blood flow and arterial pressure) to sustain normal physiological functions, there is an
optimal combination of cardiac function and arterial system status that provides the maximum efficiency in transferring this mechanical energy from the LV to the arterial tree[6]. Prior studies have demonstrated that this ideal combination occurs when the ventricle and the arterial tree are optimally coupled [7, 8].

Septic shock has a profound impact on macrohemodynamics and also the microcirculation [9, 10]. Macrocirculatory derangements in septic shock have been characterized by a combination of a variable degree of cardiac dysfunction and a profound vasoplegia [11]. These alterations are usually the expression of a ventricular-arterial uncoupling associated with a sepsis-induced cardiovascular inefficiency [9, 12]. Moreover, septic shock has also been associated with early and sustained microcirculatory derangements that may evolve independently of macrohemodynamics[13]. Since $E_{a_{dyn}}$ has been shown to be affected by both arterial and cardiac factors, we hypothesized that sepsis-induced hemodynamic cardiovascular dysfunction could affect $E_{a_{dyn}}$. We, therefore, aimed to determine the effects of endotoxin septic shock on $E_{a_{dyn}}$, and the impact of hemodynamic resuscitation.

Discussion

In this experimental animal study, $E_{a_{dyn}}$ increased during endotoxic septic shock and decreased after fluid administration. The evolution of $E_{a_{dyn}}$ was associated with both cardiac and arterial factors and cardiovascular efficiency. LPS infusion was associated with an early uncoupling between macro and microcirculation, expressed as the ratio between LV external mechanical work and tissue oxygen saturation. This condition was aggravated after hemodynamic resuscitation.

Relationship between $E_{a_{dyn}}$ and cardiac and arterial variables

We found that heart rate and $Z_c$, which represents the pulsatile component of the LV hydraulic workload related to arterial stiffness and aortic cross-sectional area[18], were the main variables associated to $E_{a_{dyn}}$ in septic animals. Moreover, when considering only HR and $Z_c$, 67% of the actual $E_{a_{dyn}}$ values could be predicted in the septic animals. However, considering the magnitude of the relationship between $E_{a_{dyn}}$ and $Z_c$ and HR, we cannot exclude that other determinants not
contemplated in our simplified arterial and cardiac models may have contributed significantly to $E_{a_{dyn}}$

These findings corroborate previous results about the compound nature of $E_{a_{dyn}}$ and the impact of both cardiac and arterial factors. While net changes in Ea, a net measure of LV afterload, were negatively associated with $E_{a_{dyn}}$, variations in heart rate did so positively [4, 30]. Our results also confirm earlier observations about the impact of endotoxic septic shock on the PPV/SVV relationship.

In a model of LPS-induced pneumonia in mechanically ventilated rats, Chenerpath et al. observed that the ratio PPV/SVV was higher in LPS-treated compared with untreated rats. Septic animals also showed a significant decrease in arterial tone, as reflected by an increase in net arterial compliance[31]. This study, together with our previous observations about the impact of changes in arterial load, support the notion that $E_{a_{dyn}}$ does not represent a real measure of central arterial tone nor an index of the arterial stiffness, and that the concept of $E_{a_{dyn}}$ as a variable describing LV afterload should be avoided[5].

**Relationship between LV energetics and $E_{a_{dyn}}$**

The force that pumps blood from the heart to the peripheral circulation is determined by an energy gradient that comprises a kinetic, gravitational, and a potential element[32]. During a contraction, the heart works increasing potential energy and, in a much smaller proportion, kinetic energy. This work is distributed to the systemic circulation generating the energy gradient that drives blood flow through to the systemic circulation and delivers adequate transport for oxygen and nutrients to the tissues. In turn, the hydraulic work generated by the ventricle can be divided into two components: steady and oscillatory work. While $W_{std}$ represents the work per unit time that effectively contributes to blood flow and peripheral perfusion, $W_{osc}$ represents the unavoidable consequence of the pulsatile nature of the heart’s activity and is considered “wasted” energy since it does not contribute to the net movement of blood to the peripheral circulation[18]. From this perspective, an efficient cardiovascular system would minimize the oscillatory component of LV mechanical work. The ratio $W_{osc}/W_{tot}$ (i.e., %Osc) becomes then a sort of index of the efficiency of the LV mechanical power
dissipation in the arterial system [24]. Moreover, as the ability of the heart as a pump for generating power depends not only on the myocardial performance but also on the physical properties of the arterial system, %Osc represents also a measure of the efficiency of the matching between the heart and the arterial system [18, 24].

While in normal conditions $\dot{W}_{osc}$ accounts only about 10% of the total LV mechanical work [24, 33], which manifests the optimal efficiency of the arterial system for buffering cardiac pulsations, factors altering arterial load or heart rate are known to affect this balance [24, 34]. In our study, the overall %Osc at baseline was $11 \pm 2\%$, similar to that reported in previous animal studies [24, 35]. While in SHAM animals %Osc remained unchanged, it significantly decreased during LPS infusion and increased after hemodynamic resuscitation. These modifications agree with the known relationship between Zc and HR and %Osc. Previous studies have shown that, when Zc decreases or heart rate increases, %Osc decreases [24, 34, 36, 37]. In our study, septic animals showed a progressive and significant decline in Zc and increased heart rate. Not surprisingly, these same factors were the main determinants of the $Ea_{dyn}$ changes in septic animals. As $Ea_{dyn}$ was directly related to $\dot{W}_{std}$ but inversely to $\dot{W}_{osc}$, $Ea_{dyn}$ reflects then not only the net LV mechanical work but how this work is generated. Therefore, changes in Osc% and EER, which expresses the energy cost for each unit of cardiac output, were inversely associated with $Ea_{dyn}$ variations. Accordingly, when cardiovascular efficiency increases, so does the $Ea_{dyn}$ [5].

Our results differ from those reported by Cholley et al. in a similar study [35]. These authors found that a lower dose of LPS (600 µg·kg$^{-1}$) resulted in a hypodynamic hemodynamic profile characterized by low cardiac output, arterial hypotension, and increased %Osc. Septic shock was also associated with a lower heart rate and higher Zc resulting from the aortic smooth muscle contraction and aortic wall edema. These discrepancies may likely reflect differences in the experimental setup, the dose of LPS, and the anesthetic regimen used (pentobarbital vs. ketamine + midazolam). However, even if our results differ in how LPS affects hemodynamics, both are coherent on the physiological mechanisms and how these factors are known to affect %Osc [24, 34, 36, 38].
Micro-macrocirculation coherence
In our study, the infusion of LPS produced a marked decrease in StO$_2$ and a mismatch between LV energetics and StO$_2$, which reflected the inability of the cardiovascular system to sustain tissue perfusion during the increased oxygen demands induced by sepsis. The overall LV mechanical power required for a given StO$_2$ during the whole experiment was 1.1 mW in SHAM animals, 1.4 mW in EDX animals, and mW in EDX-R 1.8 mW (3.1 mW after resuscitation). Therefore, even if cardiovascular efficiency improved in septic animals, this phenomenon did not lead to better tissue perfusion. Moreover, the LPS-related uncoupling between macrohemodynamics and microcirculation was aggravated after hemodynamic resuscitation. These results emphasize the known dissociation between macro and microcirculation and the futility of normalizing systemic hemodynamics when the coherence between micro and macrocirculation has been lost [39, 40].

Limitations
Our assessment of the microcirculatory perfusion was based on the regional evaluation of muscular oxygenation, which may not represent the state of the global microcirculation. However, the muscular StO$_2$ has been demonstrated to offer a proper window for early detection of the microcirculatory derangements during sepsis due to its nonvital peripheral organ condition[27]. Furthermore, our septic shock model could be considered as a representation of an early septic shock, where macro and microcirculation should be still partially coupled. In the late stages of septic shock, the evolution and interaction of macro-hemodynamic and StO$_2$ could have been different[40].

Second, the evaluation of the cardiovascular efficiency was based on the analysis of the instantaneous arterial pressure-aortic blood flow relationship [18]. This analysis, however, does not represent the actual LV mechanical efficiency since it does not consider myocardial oxygen consumption [41]. Moreover, because of our simplified assessment of LV performance, we cannot determine the actual impact of LPS on myocardial performance, which would have required the invasive measurements of LV volume and pressure. However, we have recently demonstrated that Eadyn is significantly related to ventriculo-arterial coupling and LV efficiency using the data obtained from the LV pressure-volume analysis by the classical conductance catheter technique[42]. Our
current results agree with the observations made in this study. Nevertheless, even if LPS infusion was
associated with an improved transfer of the power from the LV to the arterial system, we cannot
confirm that this condition was associated with a better myocardial contractility. As LPS can alter not
only LV contractility but also loading conditions [43, 44], the decreased arterial load in septic animals
may have played an essential role in the improved power transfer efficiency[24]: a low %Osc
indicates therefore that, for a given LV myocardial performance, the arterial load was relatively lower.
Thus, even if %Osc does not directly describe the ventricular-arterial coupling variables, it represents
the efficiency of the system[23, 25].

Finally, our study was based on the evaluation assessment of the arterial pressure and blood flow
using two independent methods for calculating PPV and SVV. The use of pulse-contour analysis for
estimating SVV and $E_{a_{dy}}$ may lead to different results, as estimations based on this methodology
may be exposed to the impact of arterial load[45] So, the usefulness of the pulse contour-derived
$E_{a_{dy}}$ would eventually depend on how the pulse contour algorithm estimates SV changes over a
respiratory cycle. If this estimation is reliable, $E_{a_{dy}}$ should be valid and reflect changes in
cardiovascular efficiency.

Conclusions
During experimental endotoxic septic shock, $E_{a_{dy}}$ changes were associated with arterial and cardiac
factors and significantly related to cardiovascular efficiency: the higher the efficiency of the
cardiovascular system on delivering the energy to the arterial system for sustaining blood flow, the
higher the $E_{a_{dy}}$. Therefore, $E_{a_{dy}}$ may be a valuable index for monitoring cardiovascular mechanical
efficiency.

List Of Abbreviations
$E_{a_{dy}}$: dynamic arterial elastance; PPV: pulse pressure variation; SVV: stroke volume variation; HR:
heart rate; CO: cardiac output; SVR: systemic vascular resistance; MAP: mean arterial pressure; C:
arterial compliance; Zc: characteristic impedance; $E_{a}$: effective arterial elastance; $R_{T}$: total mean
vascular resistance; $\tau$: diastolic time constant; LV: left ventricular; $W_{tot}$: left total ventricular power;
P: blood pressure; Q: aortic blood flow; T: cardiac period; $W_{\text{std}}$: LV steady power; $W_{\text{osc}}$: LV oscillatory power; %Osc: oscillatory power fraction; EER: energy efficiency ratio; $\text{StO}_2$: tissue oxygen saturation; NIRS: near-infrared spectroscopy; Mmi: macro-microcirculatory coupling index; SHAM: sham-operated group; EDX: endotoxic group without hemodynamic resuscitation; EDX-R: endotoxic group with hemodynamic resuscitation; LPS: lipopolysaccharide; ANOVA: analysis of variance; SE: standard error; CI: confidence interval.

Declarations

Ethics approval. All procedures and protocols in this study were reviewed and approved (project 06-04-15-230) by the Ethical Committee for Animal Experimentation of the School of Medicine of the University of Cadiz (license 07-9604) and the Dirección General de la Producción Agrícola y Ganadera of the Junta de Andalucía. Animal care and use procedures conformed to national and European Union regulations and guidelines (Spanish Royal Decree 53/2013 and EU Directive 2010/63/EU).

Consent for publication. Not applicable.

Availability of data and materials. The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests. MIMG has received Honoraria and/or Travel Expenses from Edwards Lifesciences and Deltex Medical. AGC has received Honoraria and/or Travel Expenses from Edwards Lifesciences. A.R. has received Honoraria and is on the advisory board for LiDCO, Honoraria for Covidien, Edwards Lifesciences, and Cheetah. MC in the last 5 years received Honoraria and/or Travel Expenses from Edwards Lifesciences, LiDCO, Cheetah, Bmyeye, Masimo, and Deltex. AM, PGG, MGR, and RMG have no conflict of interest to declare. The authors declare that they have no non-financial competing interests.

Funding. This work was supported by the St George’s University of London, UK, and performed at the Servicio Central de Experimentación y Producción Animal (SEPA) of the University of Cadiz, Spain.

Authors’ contributions. MIMG conceived and designed the study, participated in the experiments, performed the statistical analysis, interpreted the data, and wrote the manuscript. PGG, PSO, MGR, AGC, and JM and participated in the experiments, interpreted the data, and helped to draft the
manuscript. AM and AR have made substantial contributions to the analysis and interpretation of
data, have been involved in drafting the manuscript, and contributed to its critical review. MC
contributed to the conception and design of the study, interpreted data, and wrote and reviewed the
manuscript. All the authors read and approved the final version of the manuscript.

Acknowledgments. Dr. Carlos Costela Villodres, from the Servicio Central de Experimentación y
Producción Animal (SEPA) of the University of Cádiz, for his valuable technical assistance. Dr. Arnoldo
Santos Oviedo for his technical aid and useful comments. Medtronic/Covidien for supplying the INVOS
monitor and neonatal sensors.

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Tables
Table 1. Global hemodynamic changes during the experiment

| Variables | Baseline* | 1h | 2h | 3h | 4h³ | time interaction | group interaction | group and time interaction |
|-----------|-----------|----|----|----|----|------------------|-------------------|--------------------------|
| CO, l/min |           |    |    |    |    |                  |                   |                           |
| SHAM      | 0.49 ± 0.06 | 0.51 ± 0.03 | 0.54 ± 0.03 | 0.58 ± 0.05 | 0.59 ± 0.10 | 0.057 | vs EDX† | < 0.001 |
| EDX       | 0.54 ± 0.06 | 0.56 ± 0.07 | 0.70 ± 0.07 | 0.83 ± 0.07 | 0.81 ± 0.09 |              |                   |                           |
| EDX-R     | 0.51 ± 0.08 | 0.61 ± 0.10 | 0.77 ± 0.07 | 0.99 ± 0.14 | 1.04 ± 0.12 | < 0.001 | vs SHAM† |                   |
| SV, ml    |           |    |    |    |    |                  |                   |                           |
| SHAM      | 2.7 ± 0.4  | 2.7 ± 0.3 | 2.9 ± 0.4 | 3.1 ± 0.4 | 3.0 ± 0.6 | 0.176 |                   | 0.147 |
| EDX       | 3.0 ± 0.5  | 2.8 ± 0.5 | 3.2 ± 0.7 | 3.5 ± 0.8 | 3.5 ± 0.7 | 0.060 |                   |                   |
| EDX-R     | 3.0 ± 0.4  | 3.4 ± 0.5 | 3.6 ± 0.5 | 4.3 ± 0.6 | 4.1 ± 0.6 | 0.005 |                   |                   |
| SAP, mmHg |           |    |    |    |    |                  |                   |                           |
| SHAM      | 87 ± 13    | 76 ± 8  | 69 ± 10 | 65 ± 7  | 61 ± 6  | 0.010 | vs EDX† | < 0.001 |
| EDX       | 82 ± 11    | 62 ± 11 | 50 ± 11 | 42 ± 4  | 42 ± 5  | 0.002 | vs EDX-R† |                   |
| EDX-R     | 85 ± 13    | 61 ± 11 | 57 ± 7  | 50 ± 8  | 77 ± 10 | < 0.001 | vs SHAM |                   |
| DAP, mmHg |           |    |    |    |    |                  |                   |                           |
| SHAM      | 53 ± 6     | 46 ± 6  | 43 ± 7  | 40 ± 4  | 38 ± 3  | 0.006 | vs EDX† | < 0.001 |
| EDX       | 48 ± 6     | 41 ± 7  | 32 ± 6  | 27 ± 3  | 26 ± 3  | 0.007 | vs EDX-R |                   |
| EDX-R     | 48 ± 7     | 37 ± 5  | 35 ± 3  | 29 ± 3  | 47 ± 6  | < 0.001 | vs SHAM† |                   |
| MAP, mmHg |           |    |    |    |    |                  |                   |                           |
| SHAM      | 63 ± 7     | 55 ± 6  | 51 ± 8  | 47 ± 5  | 46 ± 3  | 0.006 | vs EDX† | < 0.001 |
| EDX       | 57 ± 7     | 47 ± 8  | 38 ± 8  | 34 ± 1  | 30 ± 3  | 0.007 | vs EDX-R† |                   |
| EDX-R     | 58 ± 8     | 45 ± 7  | 42 ± 4  | 38 ± 3  | 59 ± 5  | < 0.001 | vs SHAM† |                   |

Data are presented as mean ± standard deviation. CO: cardiac output; DAP: diastolic arterial pressure; HR: heart rate; MAP: mean arterial pressure; SAP: systolic arterial pressure; SV: stroke volume.

SHAM: sham-operated group; EDX: non-resuscitated septic rabbits; EDX-R: resuscitated septic rabbits.

* Baseline values were similar between different experimental groups.

a In the EDX-R group, 4h refers after both fluid bolus and norepinephrine infusion.

† p < 0.05 for between-group effects (Tukey-Kramer).

Table 2. Arterial variables during different stages of the experiment

| Variables | Baseline* | 1h | 2h | 3h | 4h³ | time interaction | group interaction | group and time interaction |
|-----------|-----------|----|----|----|----|------------------|-------------------|--------------------------|

Arterial load variables

Ea, mmHg/ml
### Cardiac variables

|          | HR, beats/minute | Accel, m/s² |
|----------|-----------------|-------------|
| SHAM     | 180 ± 28        | 6.47 ± 0.87 |
|          | 187 ± 26        | 6.55 ± 0.47 |
|          | 191 ± 24        | 6.58 ± 0.54 |
|          | 188 ± 21        | 7.09 ± 0.54 |
|          | 197 ± 24        | 7.02 ± 0.58 |
|          | 0.303 vs EDX †  | 0.107 vs EDX † |
| EDX      | 182 ± 20        | 6.41 ± 0.69 |
|          | 202 ± 22        | 6.19 ± 0.84 |
|          | 222 ± 29        | 6.81 ± 0.39 |
|          | 243 ± 39        | 7.29 ± 1.00 |
|          | 237 ± 39        | 6.70 ± 0.77 |
|          | 0.014 vs EDX-R  | 0.018 vs SHAM † |
| EDX-R    | 169 ± 17        | 6.95 ± 0.81 |
|          | 178 ± 15        | 6.87 ± 0.92 |
|          | 217 ± 40        | 7.51 ± 0.59 |
|          | 234 ± 41        | 8.93 ± 0.59 |
|          | 256 ± 18        | 8.96 ± 0.03 |
|          | 0.004 vs SHAM † | 1.42       |

Note: Data are presented as mean ± standard deviation.

HR: heart rate; Accel: mean acceleration of aortic blood flow; C: net arterial compliance; Ea: effective arterial elastance; SVR: systemic vascular resistance; Zc: characteristic impedance.

SHAM: sham-operated group; EDX: septic group without hemodynamic resuscitation; EDX-R: hemodynamic resuscitated septic group.

* Baseline values were similar between different experimental groups.
In the EDX-R group, 4h refers after hemodynamic resuscitation (both fluid bolus and norepinephrine infusion). † p < 0.05 for between-group effects (Tukey-Kramer).

Table 3. Effects of fluid bolus and norepinephrine in hemodynamic, tissue oxygenation, arterial variables and cardiac energetics in resuscitated septic animals (EDX-R group)

| Hemodynamic variables | 3h post-LPS | After fluid bolus (20 mL/Kg) | After norepinephrine (4h post-LPS) |
|-----------------------|-------------|------------------------------|-----------------------------------|
| CO, l/min⁻¹           | 0.99 ± 0.14 | 1.16 ± 0.09*                 | 1.04 ± 0.12†                     |
| SV, ml                | 4.3 ± 0.6   | 4.7 ± 0.6*                   | 4.1 ± 0.6                         |
| SAP, mmHg             | 50 ± 8      | 61 ± 10*                     | 77 ± 10†                          |
| DAP, mmHg             | 29 ± 3      | 35 ± 2*                      | 47 ± 6†                           |
| MAP, mmHg             | 38 ± 3      | 45 ± 4*                      | 59 ± 5†                           |
| SVV, %                | 22 ± 4      | 20 ± 3                       | 24 ± 3†                           |
| PPV, %                | 30 ± 7      | 19 ± 7*                      | 21 ± 6*                           |
| Eadyn                 | 1.38 ± 0.32 | 0.93 ± 0.24*                 | 0.87 ± 0.15*                      |
| Arterial variables    |             |                              |                                   |
| Ea, mmHg/mL·10⁻¹      | 0.16 ± 0.04 | 0.15 ± 0.03                  | 0.24 ± 0.05                       |
| C, ml/mmHg            | 0.21 ± 0.06 | 0.19 ± 0.07                  | 0.14 ± 0.03                       |
| Zc, dyn·s·cm⁻5·10⁻³   | 0.31 ± 0.12 | 0.35 ± 0.13                  | 0.45 ± 0.07                       |
| SVR, dyn·s·cm⁻5·10⁻³  | 2.32 ± 0.35 | 2.32 ± 0.27                  | 3.42 ± 0.50†                      |
| Cardiac variables     |             |                              |                                   |
| HR, beats/min         | 234 ± 41    | 251 ± 25                     | 256 ± 18                          |
| Accel, m/s²           | 8.93 ± 1.03 | 9.91 ± 0.63                  | 8.96 ± 1.42                       |
| Cardiac energetics    |             |                              |                                   |
| Wtot, mW              | 87 ± 12     | 128 ± 19*                    | 152 ± 22†                         |
| Wstd, mW              | 80 ± 10     | 115 ± 16*                    | 137 ± 20†                         |
| Wosc, mW              | 7 ± 2       | 13 ± 4                       | 16 ± 2*                           |
| Osc, %                | 9 ± 2       | 10 ± 2                       | 10 ± 1*                           |
| EER, mW·min·ml⁻¹      | 0.09 ± 0.01 | 0.11 ± 0.01                  | 0.15 ± 0.01†                      |
| Tisular perfusion variables |         |                              |                                   |
| StO₂, %               | 44.1 ± 5.2  | 49.6 ± 4.6*                  | 50.4 ± 6.8                        |
| Mmi, W/%              | 2.00 ± 0.28 | 2.60 ± 0.45*                 | 3.07 ± 0.67†                      |

Data are presented as mean ± standard deviation.
Accel: maximal acceleration of aortic blood flow; C: net arterial compliance; CO: cardiac output; DAP: diastolic arterial pressure; Ea: effective arterial elastance; Eadyn: dynamic arterial elastance; EER: energy efficiency ratio (Wtot/CO); HR: heart rate; LPS: lipopolysaccharide; MAP: mean arterial pressure; Mmi: macro-microcirculatory...
Table 4. Relationship between Ea\textsubscript{dyn} and arterial load, cardiac variables, cardiac energetics, LV efficiency and peripheral perfusion indexes according to a mixed-effect regression model in septic animals (EDX and EDX-R).

| Fixed effects          | Estimate (95% confidence interval) | p value |
|------------------------|-----------------------------------|---------|
| **Arterial load**      |                                   |         |
| SVR, dyn·s·cm\textsuperscript{-5}·10\textsuperscript{3} | 0.009 (-0.056 – 0.075) | 0.770   |
| C, ml/mmHg             | 0.509 (-1.534 – 2.552)            | 0.611   |
| Zc, dyn·s·cm\textsuperscript{-5}·10\textsuperscript{3} | -1.053 (-1.896 – -0.209) | 0.017   |
| **Cardiac variables**  |                                   |         |
| Heart rate, beats/min  | 0.006 (0.003 – 0.008)             | <0.001  |
| Accel, ms/s\textsuperscript{2} | 0.047 (-0.044 – 0.137) | 0.301   |
| **Cardiac energetics** |                                   |         |
| \(\dot{W}_{\text{std}}\), W | 0.017 (0.007 – 0.027) | <0.001  |
| \(\dot{W}_{\text{osc}}\), W | -0.125 (-0.174 – -0.076) | <0.001  |
| **Cardiovascular efficiency** |                                 |         |
| %Osc                   | -0.101 (-0.137 – -0.064)          | <0.001  |
| EER, W·s·ml\textsuperscript{-1} | -9.494 (-11.964 – -7.024) | <0.001  |

Accel: maximal acceleration of aortic blood flow; C: arterial compliance; Ea\textsubscript{dyn}: dynamic arterial elastance; EER: energy efficiency ratio; Mmi: macro-microhemodynamic coupling index (\(\dot{W}_{\text{tot}}/\text{StO}_2\)); PV: peak velocity of aortic blood flow; SVR: systemic vascular resistance; \text{StO}_2: tissular oxygen saturation; \(\dot{W}_{\text{osc}}\): left ventricular oscillatory work; \(\dot{W}_{\text{std}}\): left ventricular steady work; Zc: characteristic impedance; %Osc: oscillatory power fraction.

Estimates reflect the average change in Ea\textsubscript{dyn} per unit increase of the fixed covariate. Mixed-effect regression models were constructed using arterial variables (SVR, C and Zc), cardiac variables (HR and Accel), cardiac energetic variables (\(\dot{W}_{\text{std}}\) and \(\dot{W}_{\text{osc}}\)), %Osc, EER, as independent variables.
Figure 1

Calculation of pulse pressure variation (PPV), stroke volume variation (SVV), and dynamic arterial elastance (Eadyn). From top to bottom: aortic blood flow (blue); femoral arterial pressure (red); beat-to-beat stroke volume and arterial pulse pressure (pink and dark blue); stroke volume variation (SVV, dotted red line), pulse pressure variation (PPV, blue dashed line) and dynamic arterial elastance (Eadyn, solid green line).
Calculation of left ventricular energetics. Aortic blood flow (top left, blue line) and arterial pressure waveforms (top right, red line) were ensembled-averaged (bottom, left) for analysis. The total LV power ($W_{tot}$) transferred to the systemic circulation was calculated as the time-averaged integral of the instantaneous product of pressure and flow during the whole cardiac period (bottom right, green shaded area). The difference between total power ($W_{tot}$) and steady power ($W_{std}$, solid line) represents the extra expenditure of energy imposed by the pulsatile nature of the heart, i.e., the oscillatory power ($W_{osc}$, dashed line).
Evolution of arterial pressure-flow relationship. Example of the evolution of blood flow (left column) and arterial pressure waveform (middle column) and the pressure-flow loops (right column) in three animals from sham-operated group (SHAM), endotoxic group (EDX), and hemodynamic-resuscitated endotoxic group (EDX-R) during the study. In this latter group,
4h stage refers to after both fluid bolus and norepinephrine infusion. Pressure-flow loops were constructed using data from the shown aortic blood flow and arterial pressure waveforms on each experimental stage.
Figure 4

Evolution of left ventricular energetics. Changes in left ventricular total work (\(\dot{W}_{\text{tot}}\)), steady power (\(\dot{W}_{\text{std}}\)), oscillatory power (\(\dot{W}_{\text{osc}}\)) and oscillatory power fraction (Osc) in the three experimental groups: Experimental arms: sham-operated group (SHAM), resuscitated endotoxic group (EDX), and hemodynamic-resuscitated group (EDX-R). Values are presented as mean ± SD. Differences in time course between groups: * \(p < 0.05\).
Evolution of tissue oxygen saturation (StO2), energy efficiency ratio (EER) and macro-microcirculatory coupling index (Mmi). Experimental arms: sham-operated group (SHAM), resuscitated endotoxic group (EDX), and hemodynamic-resuscitated group (EDX-R). Values are presented as mean ± SD. Differences in time course between groups: * p < 0.05.

Evolution of dynamic arterial elastance, pulse pressure variation (PPV) and stroke volume variation (SVV). Experimental arms: sham-operated group (SHAM), resuscitated endotoxic group (EDX), and hemodynamic-resuscitated group (EDX-R). Values are presented as mean ± SD. Differences in time course between groups: * p < 0.05.

Supplementary Files
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