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REVIEW ARTICLE

Ventriculo-arterial coupling: from physiological concept to clinical application in peri-operative care and ICUs

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As an extension of the traditional heart-centred pressure-flow model, the ventriculo-arterial coupling concept is based on the pressure–volume relationship of the left ventricle and the vascular system. Even though ventriculo-arterial coupling has been studied in cardiology for more than 30 years, its value in clinical practice in anaesthesia and ICU remains poorly known and used.

The clinical interest in ventriculo-arterial coupling is derived from its strong connection with cardiac energetics and efficiency. An alteration of ventriculo-arterial coupling is a marker of disease severity and is associated with outcome. The main categories of cardio-circulatory failures observed in ICU patients commonly exhibit alterations in ventriculo-arterial coupling with typical patterns. Furthermore, the effectiveness of usual haemodynamic treatments and interventions correlates with ventriculo-arterial coupling improvements in ICU patients. Consequently, treatment and management bundles may be proposed to specifically target the correction of ventriculo-arterial uncoupling to optimise the patients' haemodynamic status and outcome. Restoring ventriculo-arterial coupling with treatments improves outcomes in subgroups of ICU patients.

Even though ventriculo-arterial coupling evaluation cannot be considered as a part of the basic core curriculum of anaesthesiologists and ICU residents, anaesthesia and ICU practitioners must be familiarised with the clinical significance of ventriculo-arterial (un)coupling and availability of its bedside noninvasive evaluation. The understanding of ventriculo-arterial coupling may be particularly important in complex haemodynamic clinical situations.

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KEY POINTS

- Ventriculo-arterial coupling is a concept that describes the interaction of the left ventricle and the vascular system in terms of volume/pressure relationship.
- Ventriculo-arterial coupling is estimated as the ratio of two elastances: arterial elastance and ventricular elastance.
- The main categories of cardio-circulatory failures observed in intensive care patients commonly exhibit typical patterns of alteration in ventriculo-arterial coupling.
- Restoring ventriculo-arterial coupling with haemodynamic treatments improves tissue perfusion and outcomes in subgroups of intensive care patients; however, further studies are necessary.

Introduction

Even though ventriculo-arterial coupling has been studied and used in clinical practice in cardiology for more than 30 years, its relevance in anaesthesia and ICU remains poorly known and used. Anaesthesiologists/intensivists have to deal with several haemodynamic alterations and circulatory abnormalities requiring integrated knowledge of physiology/pathophysiology of the cardiovascular system. In the classic haemodynamic approach, the heart and the arterial system are described as

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distinct structural and functional entities. Variables, such as cardiac output (CO) and mean arterial pressure, are analysed separately in many situations, and their interactions are rarely numerically described. However, the heart and the arterial vascular tree, including the aorta, are interdependent systems that are complementary and sometimes competitive. All compartments contribute to overall cardiovascular system homeostasis and performance, although no compartment function can be modified without altering the other. Ventriculo-arterial coupling is a physiological concept that describes the interaction of the left ventricle (LV) and the arterial system (principally the aorta). Noninvasive methods to assess ventriculo-arterial coupling are now available at the bedside.[1] Complementary to the haemodynamic approach based on cardiac efficacy (i.e. maximisation of CO), ventriculo-arterial coupling assessment confers an insight into cardiac efficiency, which is the energy required to provide a defined output.

In the era of personalised medicine, opportunities for haemodynamic optimisation must be considered. In this respect, ventriculo-arterial coupling concepts and clinical estimators used in anaesthesia and in the ICU can be regarded as novel.

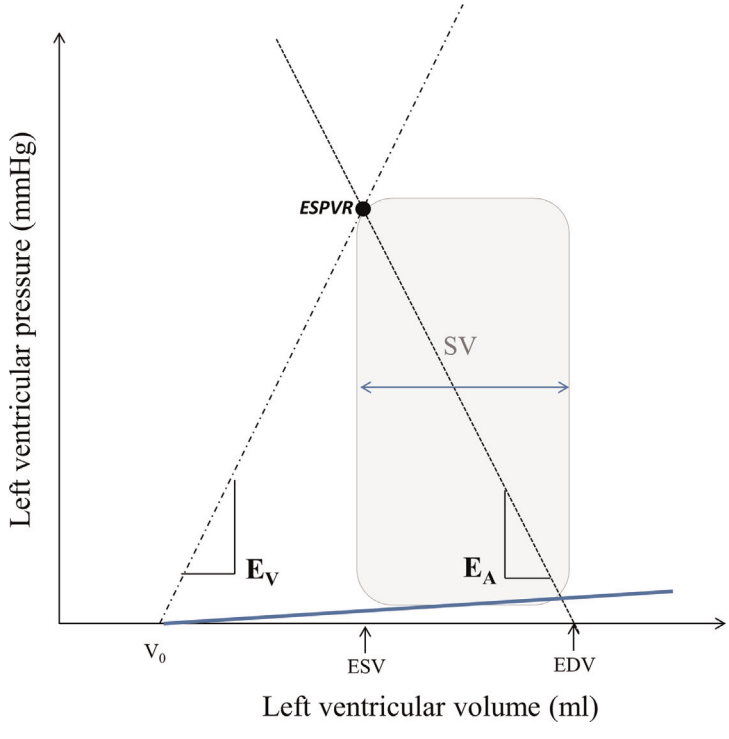
Definitions that build operational knowledge of ventriculo-arterial coupling

Determinants of ventriculo-arterial coupling

Functionally, the heart and the arteries adapt to each other during the cardiac cycle to generate CO and blood pressure.[2] This statement is true for the right ventricle/pulmonary artery and LV/aorta coupling. In this article, the term ventriculo-arterial coupling is restricted to the LV/aorta.[3] The LV pumps a blood volume during a cardiac cycle that is ejected into the arterial system (aorta). The arterial system represents a load opposed to the ejection of blood from the heart and modulates its performance and energetics. Ventriculo-arterial coupling refers to this interaction during the cardiac cycle of the LV with the arterial system. In other words, the systole–diastole succession concerns not only the cardiac pump but also the vascular system. The ventriculo-arterial coupling is based on an integrated pressure–volume relationship of the LV and arterial system.[4–7] Ventriculo-arterial coupling is estimated as the ratio of two elastances: the arterial elastance (E_A) and LV elastance (E_V) (ventriculo-arterial coupling = E_A/E_V, Fig. 1).

The E_V, specifically the end-systolic E_V, is a characteristic of cardiac function, contractility and morphology

FIGURE 1 Left ventricular pressure–volume curve. EDV, left ventricular end-diastolic volume (ml); ESPVR, end systolic pressure volume relationship; ESV, left ventricular end-systolic volume (ml); SV, stroke volume (ml).



E_V is the slope of the line connecting V_0 to the ESPVR

Load independant ventricular function
E_V = 2.3 +/- 1 mmHg ml^{-1}

E_A is the slope of the line connecting the LV end-diastolic volume to the ESPVR

Vascular function : pulsatile and continuous component of arterial load
E_A = 2.2 +/- 0.8 mmHg ml^{-1}

● Ventriculo-arterial coupling :
E_A/E_V : 1 +/- 0.36

and is independent of preload and afterload.[8] The E_V can be derived from the LV pressure-volume loop (PVL) for a given beat-to-beat preload and afterload. The PVL is based on the linear relationship between the end-systolic ventricular pressure and the end-systolic LV volume: the end-systolic pressure–volume relationship (ESPVR) (Fig. 1). The E_V represents the necessary intracavitary pressure required to increase its volume by one unit ($mmHg\,ml^{-1}$ = elastance).[1] The E_V is the slope of the line connecting V_0 to the ESPVR. V_0, which is the volume–axis intercept of the linearly projected ESVPR, to the ESPVR. V_0 represents a theoretical left ventricular volume at zero intracavitary pressure. In humans, the normal value of E_V is 2.3 $\pm$ 1 $mmHg\,ml^{-1}$.[9,10]

The arterial load represents all extra-cardiac forces opposed to left ventricular ejection: the arterial afterload. The best parameter for describing these forces may be the aortic input impedance, but it is assessed in the frequency domain. To overcome this issue, we can describe the arterial load by the slope of the relationship between the stroke volume (SV) and end-systolic arterial pressure: the arterial effective elastance (E_A). E_A does not actually represent the elastance of a specific segment of the arterial tree but a cumulative parameter of the entire arterial system. E_A represents arterial function, and it can be assimilated to the net arterial load characterised by the total peripheral resistance, characteristic impedance and systolic and diastolic time intervals.[8,11]

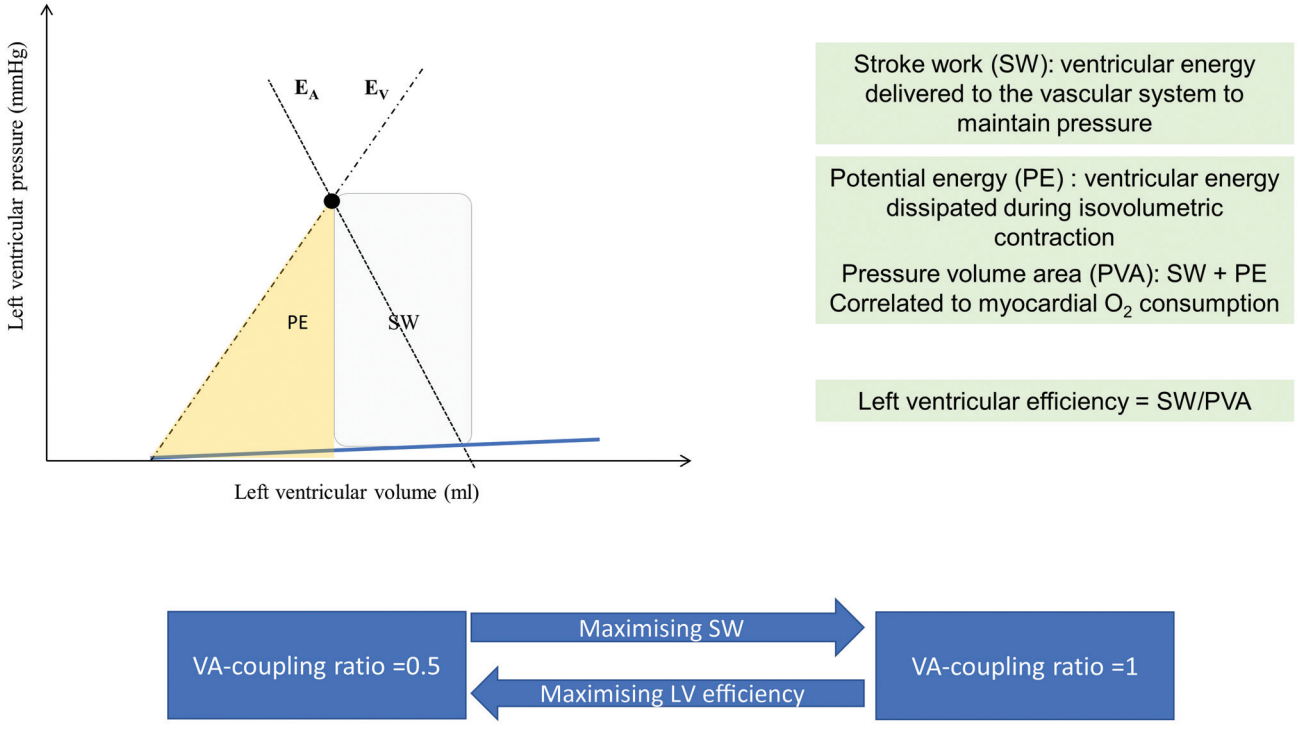
$$E_A = R_t[t_s + \tau \times (1 - e^{-td/\tau})]$$

where t_s and t_d are the systolic and diastolic periods, respectively. R_t is the total mean vascular resistance (peripheral resistance and characteristic impedance), and τ is the diastolic time constant.

Evidently, on the basis of the above formula, the restrictive use of systemic vascular resistance to estimate the behaviour of the arterial system is simplistic. E_A can also be represented as the slope of the line connecting the left ventricular end-diastolic volume to ESPVR[1] (Fig. 2). In humans, the normal value of E_A is 2.2 $\pm$ 0.8 $mmHg\,ml^{-1}$.[9,12]

In humans, the mean value of E_A/E_V ratio is 1 $\pm$ 0.36.[9,12] Consequently, an uncoupled value indicates a ratio of elastances outside this range. Ventriculo-arterial uncoupling can be due to the results of alterations of E_A, E_V or both. Importantly, ventriculo-arterial coupling may be preserved despite considerably altered values of E_A and E_V, and therefore, a complete analysis of ventriculo-arterial coupling requires the analysis and interpretation of all components (i.e. E_A, E_V and E_A/E_V).

FIGURE 2 Left ventricular pressure–volume loop.



KEY POINTS

E_V is the slope of the line connecting V_0 to the ESVPR. It is a (nearly) load-independent left ventricular function parameter. Normal values for $E_V = 2.3 \pm 1\,mmHg\,ml^{-1}$.

E_A is the slope of the line connecting the left ventricular end-diastolic volume to the ESPVR. It is a vascular function parameter that integrates the pulsatile and continuous components of the arterial load. Normal values for $E_A = 2.2 \pm 0.8\,mmHg\,ml^{-1}$.

Ventriculo-arterial coupling is the ratio E_A/E_V, and the normal values are 1 ± 0.36.

A complete evaluation of ventriculo-arterial coupling requires the analysis of all three parameters: E_A, E_V and E_A/E_V.

Relationship of ventriculo-arterial coupling with left ventricular energetics

The efficacy and efficiency of the cardiovascular system are the result of regulated interactions between the heart and the vascular system. Cardiovascular performance can not only be evaluated in terms of efficacy (blood pressure and blood flow) but also in terms of efficiency (i.e. energetic cost for the cardiovascular system to provide the same blood pressure and blood flow). Ventriculo-arterial coupling represents a clinical parameter of cardiovascular efficiency. Ventriculo-arterial coupling adequacy is one of the main determinants of myocardial energetics during the transfer of an SV from the heart to the arterial system in a beat-to-beat interplay between left ventricular contractility and arterial load.

From any given ventricular PVL, different energy measures can be obtained: stroke work and potential energy (Fig. 2).[13] The total energy consumed during the cardiac cycle is the sum of stroke work and potential energy, which is designated on the PVL as the pressure–volume area (PVA).[13] The PVA is linearly correlated to myocardial oxygen consumption.[13] Stroke work is the effective left ventricular energy that may be transmitted to the arterial system. Potential energy signifies the dissipated energy during the left ventricular isovolumetric contraction. Left ventricular efficiency is the ratio between stroke work and PVA. Stroke work is calculated as ESPVR × SV. Potential energy is calculated as ESPVR × ((ESV − V_0)/2) and assumes that V_0 is negligible compared to ESV.[13]

Left ventricular efficiency is maximised during normal physiological situations with an E_A/E_V of 0.5. During stressful haemodynamic situations, stroke work is maximised, reaching a maximum E_A/E_V ratio of 1.[1] The energetic balance of the cardiovascular function is optimal when E_A/E_V is 1, whereas at a ratio of 0.5, maximal cardiac efficiency is observed.[14] An alteration in this ratio is both a marker of disease severity and an independent predictor of outcome in cardiovascular diseases.[15–18] Ventriculo-arterial coupling is a parameter of cardiac work efficiency. Most literature performed in ICU and anaesthesia concerning haemodynamic alterations and their correction focuses on the efficacy of the cardiovascular system (its performance). Efficiency, which is the myocardial energy expenditure necessary for a given cardiac output and vascular performance, is rarely considered.

KEY POINTS

Left ventricular stroke work: Left ventricular energy delivered to the arterial system to maintain pressure

Potential energy: Left ventricular energy dissipated during isovolumetric relaxation

PVA: stroke work + potential energy, linearly correlated to myocardial O_2 consumption

Left ventricular efficiency = stroke work/PVA

Measurement of the left ventricular-arterial coupling at bedside

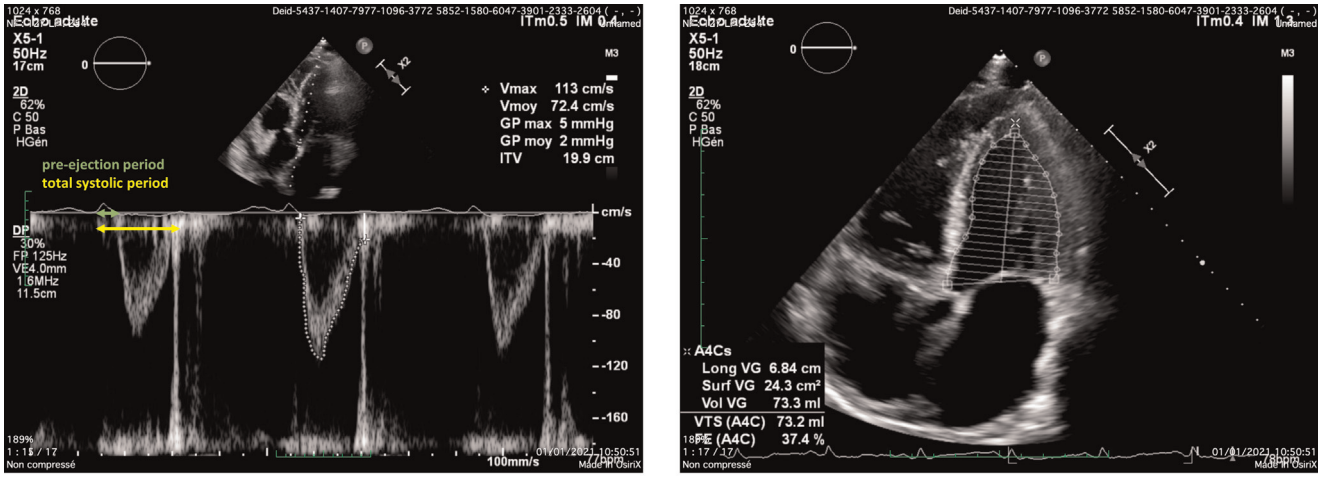
The gold standard for measuring ventriculo-arterial coupling is the invasive measurement of ventricular volumes and pressures to assess PVL and to calculate E_A and E_V.[14] This invasive method requires the use of a conductance catheter and the manipulation of the loading conditions to obtain E_V from multiple heartbeats; however, this method is not feasible in clinical practice. Several noninvasive single-beat methods have been developed and validated against the multiple-beat gold standard method to overcome this problem.[19,20] None of these methods are interchangeable,[20] requiring the use of the same method to evaluate the effects of interventions on ventriculo-arterial coupling. E_A and E_V can be measured using noninvasive cardiac echography coupled with blood pressure measurements.

The simplest method is:

$$E_v = 0.9 \times \text{systolic arterial pressure}/\text{left ventricular end-systolic volume}^{20}$$

The recommended method is the single-beat method, which was developed by Chen *et al.* (Fig. 3).[1,21] Chen's method is based on measurements of diastolic arterial blood pressure, systolic arterial blood pressure,

FIGURE 3 Chen's single-beat method was used to calculate ventricular elastance.



$$E_v = (DAP - [End(est) \times SAP \times 0.9)] / End(est) \times SV$$

$$End\ (est) = 0.0275 - 0.165 \times LVEF + 0.3656 \times (DAP/SAP \times 0.9) + 0.515 \times End\ (avg)$$

$$End\ (avg) = 0.35695 - 7.2266 \times tNd + 74.249 \times tNd^2 - 307.39 \times tNd^3 + 684.54 \times tNd^4 - 856.92 \times tNd^5 + 571.95 \times tNd^6 - 159.1 \times tNd^7$$

An Iphone application (iElastance) can be used to easily calculate ventricular elastance. DAP, diastolic blood pressure; End, estimated normalised ventricular elastance; LVEF, left ventricular ejection fraction; SAP, systolic blood pressure; SV, stroke volume; tNd, ratio of preejection period to total systolic period.

SV, left ventricular ejection fraction and the estimated normalised ventricular elastance (End).

$$E_v = (DAP - [End(est) \times SAP \times 0.9)] / End\ (est) \times SV$$

DAP: diastolic blood pressure; SAP: systolic blood pressure; SV: stroke volume; End: estimated normalised ventricular elastance; t: the ratio of the pre-ejection period to the total systolic period.

End average is calculated by a polynomial formula based on pre-ejection and ejection times. This method has the vulnerability of maximising errors in measures.[1] Another limit is the premise that End is nearly constant and unaffected by different physiological conditions or cardiac diseases, which have not yet been fully validated.

E_A calculation is based on the SV and end-systolic pressure measurements. End-systolic pressure can be estimated as 90% of the SAP, as the mean aortic pressure or as the aortic dicrotic notch pressure.[22] Some haemodynamic devices (MOSTCARE^{TM}) already integrate the calculation of E_A as the peripheral dicrotic notch pressure to SV ratio. Given that the accuracy of this measure may depend on the arterial site measurements and underlying disease, the estimation of end-systolic pressure based on MAP may offer a better surrogate over different haemodynamic conditions and when measured interchangeably in any peripheral arterial site.[22]

$$E_A = 0.9 \times SAP/SV = MAP/SV = MAP \times HR/CO = HR \times \text{peripheral resistances}$$

MAP: mean arterial pressure; SAP: systolic arterial pressure; SV: stroke volume; HR: heart rate; CO: cardiac output; × designates multiplication

Continuous monitoring of ventriculo-arterial coupling: A place for dynamic arterial elastance

Dynamic arterial elastance (Ea_{dyn}) is the ratio of respiratory variation of pulse pressure to respiratory variation of SV.[23] Ea_{dyn} can be measured with several haemodynamic monitors (MOSTCARE, PICCO)^{TM} or with cardiac echography. Given that its measure is based on the relationship between SV and pulse pressure, Ea_{dyn} may be an indicator of ventriculo-arterial coupling. An animal study that manipulated preload, afterload and inotropism demonstrated an association between Ea_{dyn} and ventriculo-arterial coupling.[24] Subsequently, Ea_{dyn} has been demonstrated to be associated with oscillatory power fraction and energy efficiency ratio in septic shock. In this manner, Ea_{dyn} can be used as an indicator of

cardiovascular efficiency. Such an association has not been demonstrated in humans during norepinephrine administration.[25] Underlying disease and haemodynamic treatment may affect the relationship between SV, pulse pressure and ventriculo-arterial coupling.[26–29] Several studies have demonstrated the ability of the Ea_{dyn} to predict successful norepinephrine weaning and thus decrease the time exposure to the vasopressor.[25–29] This index has been integrated in haemodynamic algorithms to predict further intra-operative hypotension with good predictive value.[30] In summary, Ea_{dyn} can be used to understand the interaction between cardiac function and arterial load and the effects of haemodynamic treatment on arterial load components and thus to determine which treatments can be used or withdrawn.[27–29] Presumably, asserting that Ea_{dyn} is a clinically acceptable surrogate of ventriculo-arterial coupling under all pathophysiological conditions and for all patients admitted to intensive care or in the peri-operative period is currently inappropriate. Before the widespread use of the Ea_{dyn}, we must have more interventional studies regarding this parameter.

Ventriculo-arterial coupling in different contexts

In anaesthesia practice

There are limited data on the effects of commonly used anaesthetic drugs on ventriculo-arterial coupling. Pittarello *et al.*[31] demonstrated that despite a decrease of E_A and E_V with remifentanil, ventriculo-arterial coupling remains unchanged. A study evaluating the effects of general anaesthesia with propofol/remifentanil infusion and positive pressure ventilation demonstrated a decrease in E_V with the induction of anaesthesia and a trend for a decrease in E_A; ventriculo-arterial coupling is globally unchanged.[32] Given that anaesthetic drugs can alter vascular properties, they can alter the E_A, with a reduced effect on E_V.[33]

In acute care and intensive care practice

Intensive care practitioners have to manage different states of acute cardio-circulatory dysfunction/failure, implying alterations of E_A, E_V or both. Large-scale prevalence epidemiological data on ICU patients are not available; however, ventriculo-arterial uncoupling is likely in these clinical contexts and as suggested by various studies.[16–18,34] The phenotypes of cardio-circulatory failure with proposed mechanisms of potential ventriculo-arterial uncoupling are presented in Table 1 and discussed briefly in the following section.

Heart rate values and ventriculo-arterial coupling

Given that E_A is modulated by systolic and diastolic times, any changes in heart rate must be able to change its value. In healthy dogs, an increase in heart rate during exercise is associated with an increase in E_V, which can match with E_A in maintaining nearly optimal ventriculo-arterial coupling.[35] This effect is known as the force–frequency relationship of the ventricle (the Bowditch effect), which is an intrinsic property of cardiac muscle. This effect is altered in heart failure.[36] In such situations, ventriculo-arterial coupling is altered at rest, and any increase in heart rate values exacerbates ventriculo-arterial uncoupling because E_A is not counterbalanced by an increase in E_V.[36]

Hypovolaemia

Hypovolaemia is a common acute care situation characterised by ventriculo-arterial uncoupling through high E_A induced by sympathetic activation to maintain tissue perfusion.[34] In this case, severe tachycardia may further increase E_A and aggravates the ventriculo-arterial uncoupling.[36]

Vasoplegic syndrome

Vasoplegic syndrome is another type of cardio-circulatory instability of different inflammation-mediated causes

TABLE 1 Ventriculo-arterial coupling and its determinants in common cardio-circulatory failure.

Cardiocirculatory failure	Phenotype	E_V	E_A	E_A/E_v ratio
Vasoplegia		~	↓↓	↓↓
Sepsis	Hyperkinetic	~	↓↓	↓↓
	Normokinetic	~/↓	~/↓	~/↑
	Hypokinetic	↓↓	~/↑	↑
Left heart failure	Systolic heart failure	↓↓	~/↑	↑
	'Diastolic' heart failure (heart failure with preserved ejection fraction)	↑	↑	~/↑
	Cardiogenic shock	↓↓↓	~/↓↓	↑↑
Right heart failure	Pulmonary embolism	~/↑	↑	↑
	Pulmonary hypertension	~/↑	↑	↑
	Ischemic	↓↓	↑	↑
Tachycardia		~/↑	↑↑	~/↑
Severe arterial hypertension		~/↓	↑↑	↑
Hypovolemia		~	↑↑	↑
Trauma	Haemorrhage	~/↓	↑↑	↑
	Systemic inflammatory response syndrome	~	↓↓	↓
Anaphylaxis		~	↓↓	↓

Compiled from ref.[6–51]

that is frequently seen in ICU patients. This syndrome is usually observed in sepsis, polytrauma, anaphylaxis or after major cardiac and non-cardiac surgeries.[37–40] Vasoplegic syndrome is characterised by several alterations of vascular homeostasis that lead to severe arterial hypotension with low systemic vascular resistance, altered arterial compliance[41] and changed pulse wave velocity propagation. In general, cardiac output is maintained or increased, but it can be altered. From a physiological perspective, vasoplegic syndrome concerns only the vascular component, which is E_A, with a high E_A/E_V ratio. The ventricular function (i.e. E_V) is not altered. In clinical practice, ventricular function (i.e. E_V) can be altered by the underlying process (e.g. sepsis-induced myocardial depression) and/or by myocardial dysfunction in relation to arterial hypotension or dyssynchrony.[39,42,43]

Sepsis

Sepsis is not a homogeneous entity in terms of haemodynamic phenotypes. Several clinical haemodynamic phenotypes have been described.[44,45] The prevalence of ventriculo-arterial uncoupling in sepsis has not yet been evaluated in large cohorts of patients. From published studies, approximately 70% of patients with septic shock may have ventriculo-arterial uncoupling.[40,42,46,47] Shock alteration plays a central role in vascular properties with severe vasoplegia.[48] Nevertheless, the decrease in E_A (hyperkinetic phenotype) is not the only pattern observed in sepsis. A hypokinetic phenotype, with a decrease in left ventricular function (E_V), can also be observed. The normokinetic phenotype is associated with less E_A and E_V alterations. In resuscitated patients with sepsis, persistent tachycardia can be a supplementary factor of ventriculo-arterial uncoupling by decreasing diastolic filling (thus reducing cardiac output), which is associated with increased mortality.[49] Moreover, fluid infusion and vasopressive and inotropic drugs can further alter vascular properties and cardiac function, thus modifying E_A, E_V and ventriculo-arterial uncoupling.[41]

Acute left-sided heart failure

Acute decompensated heart failure is characterised by a high E_A/E_V ratio, which is caused by high E_A and low E_V.[50] Because of low E_V, patients are highly sensitive to E_A, particularly through high heart rate values.[51] Tachycardia, in the context of heart failure, is associated with an increase in E_A because of a decrease in diastolic time and vascular compliance.[36,52] Moreover, as previously stated, the increase in E_A cannot be counterbalanced by an increase in E_V; the frequency potentiation of contractile function is decreased in the failing heart. Cardiogenic shock is the most severe form of circulatory failure. It is associated with a severe decrease in E_V and an initial increase and then a decrease in E_A.[53–55] Ventriculo-arterial coupling utility is debated in the context of acute heart failure with a preserved ejection fraction. In this clinical situation, a concomitant increase in both E_A (increased stiffness) and E_V (cardiac hypertrophy and remodelling) occurs, making their ratio, but not their individual values, less meaningful.[1] However, some studies have suggested a heterogeneity in this population, with the existence of a subgroup with high E_V and less unchanged E_V relation.[51]

Clinical relevance of ventriculo-arterial coupling evaluation and manipulation

Clinical outcomes

In chronic cardiovascular diseases, the main effective therapeutic interventions have been demonstrated to improve ventriculo-arterial coupling, thus affecting clinical outcomes (Table 2).[1] Several studies in acute heart failure have demonstrated an improvement in ventriculo-arterial coupling by inotropes and/or inodilators.[53–59] During refractory cardiac failure, some patients require extracorporeal membrane oxygenation (ECMO). Veno-arterial femoro-femoral ECMO implantation with resulting retrograde ECMO arterial flow, in the clinical context of already impaired ventriculo-arterial coupling, is associated with further alteration of ventriculo-arterial coupling because of an increase in E_A (low SV and high retrograde blood pressure).[60,61] In this context, the use of a microaxial nonpulsatile aortic assistance is associated with improved ventriculo-arterial coupling by decreasing E_A and slightly increasing E_V.[62] Veno-arterial axillary EMCO implantation can avoid the deleterious effects of retrograde arterial flow.[63]

For ICU patients, ventriculo-arterial uncoupling is not an incidental finding, as it is an independent predictor of morbidity and mortality in several settings (e.g. septic shock and cardiac ICU trauma).[15,16,64] In a cohort of trauma patients admitted to the ICU, survivors show a better ventriculo-arterial coupling ratio than nonsurvivors, which is explained by reduced E_A and increased Ev.[65] Chang *et al.*[66] further suggested that a haemodynamic optimisation approach based on improved ventriculo-arterial coupling is associated with improved

TABLE 2 Main effects on determinants of ventriculo-arterial coupling of the therapeutics used in acute care

Treatment	Effects E_A	E_V
Inotrope/inodilator	↓	↑↑
Phenylephrine	↑↑	∼↓
Norepinephrine	↑↑	↑
Epinephrine	↑↑	↑
Vasodilator	↓	∼
Volume expansion	↓	∼
Beta-blocker	↓	∼↓
Loop diuretics and decongestion	↓	∼
VA-ECMO (retrograde arterial flow)	↑	∼↓
Axial pump flow (LV unloading)	↓	∼↑

tissue perfusion and less organ dysfunctions. Ventriculo-arterial coupling may be associated with VO_2 changes in ICU patients.[17] Interestingly, VO_2 responders are characterised by improvement in ventriculo-arterial coupling, indifferently of the used haemodynamic intervention.[17] Recently, a randomised pilot study demonstrated the feasibility of optimising ventriculo-arterial coupling in the early phase of patients with septic shock.[18] Such an approach appears promising because it has been associated with improved lactate clearance and a trend to reduce mortality. Further randomised studies are needed to confirm these results.

Effects of haemodynamic therapeutics on ventriculo-arterial coupling

Several studies evaluating the effect of cardiovascular therapeutics (e.g. volume expansion, norepinephrine and inotropes) demonstrated an association between ventriculo-arterial coupling status and the clinical effect of each intervention. These therapeutic interventions, by improving ventriculo-arterial coupling, restore blood pressure and blood flow and possibly improve cardiac energetics (see above). Preload-dependent patients have a high baseline ventriculo-arterial coupling ratio in relation to high E_A. Volume expansion improves ventriculo-arterial coupling by decreasing E_A, and in some cases (patients with sepsis), by increasing E_V.[34] The ventriculo-arterial coupling may be connected to the role of systemic E_A changes in maintaining SV after volume expansion.[67,68]

Patients with congestive acute decompensated cardiac failure have shown improved ventriculo-arterial coupling after diuretic therapy.[50] In septic and nonseptic vasoplegia, patients are characterised by ventriculo-arterial uncoupling in relation to high E_A and low E_V. Despite an increase in blood pressure with norepinephrine administration, only patients who have shown improved E_A/E_V ratio have also increased their CO, thus improved tissue perfusion.[39,47] The potential benefit of esmolol in resuscitated patients with sepsis may be explained by its effect on heart rate and E_A, thus ventriculo-arterial coupling.[49] Another aspect of the clinical relevance of ventriculo-arterial coupling in ICU is illustrated by the management of blood pressure in patients supported by norepinephrine.[69] The use of vasopressor-weaning algorithm based on dynamic E_A has decreased the duration of exposure to vasopressor while also improving tissue perfusion.[26]

Implementation of clinical reasoning around the ventriculo-arterial coupling concept

At present, no study has demonstrated the clinical benefit (improved survival) of haemodynamic algorithms that include ventriculo-arterial coupling. One pilot study performed in patients with sepsis highlighted the potential clinical benefit of early haemodynamic optimisation based on ventriculo-arterial coupling. In this study, patients who were optimised showed improved lactate clearance, with a trend towards decreased mortality. The ideal haemodynamic treatment in patients with acute circulatory failure targets an increase in effectiveness without altering efficiency (i.e. a E_A/E_V ratio close to 1; Fig. 2).[13]

The objective of haemodynamic optimisation based on ventriculo-arterial coupling is to measure ventriculo-arterial coupling (i.e. E_A/E_V ratio), to analyse each component (E_A, E_V) regarding the clinical context (e.g. cause, treatment and so on) and to obtain a ventriculo-arterial coupling ratio close to 1 by using the right treatment option (Table 3, Fig. 4).[17] The knowledge of physiology is the first step to use correct pathways of management of complex ICU scenarios. We can illustrate these points with specific clinical situations, such as acute circulatory failure in the context of cardiogenic shock (Fig. 4) or norepinephrine weaning.

Conclusion

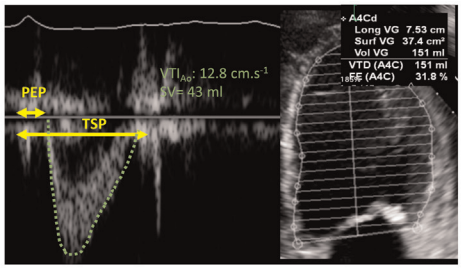
Ventriculo-arterial coupling is a concept based on the understanding that the cardiac pump and arterial system 'work together' in an integrated manner. The ventriculo-arterial coupling represents a clinical parameter of cardiovascular efficiency associated with cardiovascular performance and clinical outcome, with limited but promising evidence to date. In anaesthesia and intensive care practice, ventriculo-arterial coupling is still considered as 'novel' and approached as a research tool. The tools for ventriculo-arterial coupling estimation in routine anaesthesia/intensive care practice, although complex, are now available. The manipulation of ventriculo-arterial (un)coupling may be a part of bedside-available therapeutic strategies aimed at improving outcomes in selected clinical scenarios.

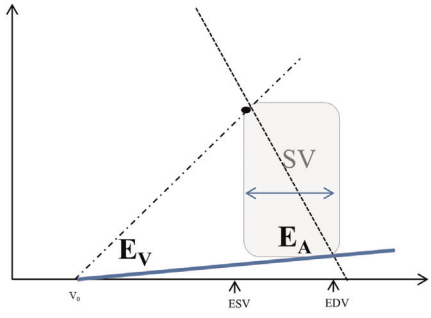
TABLE 3 Hemodynamic orientation and therapeutic options in ventriculo-arterial uncoupling (i.e. E_A/E_V ratio >1.36).

E_A	E_V	Hemodynamic characteristics	Treatment option
High	Normal	Preload dependence, high blood pressure, tachycardia	Volume expansion, vasodilator, beta-blocker
High	Low	Low inotropic function, high blood pressure, tachycardia, congestion	Inodilator, vasodilator, beta-blocker if possible, diuretics
Low	Normal or high	Low blood pressure	Vasopressor
Low	Low	Low inotropic function, low blood pressure	Vasopressor, inotrope

FIGURE 4 Adjustment of norepinephrine in cardiogenic shock based on VA-coupling. Panel A: before. Panel B: after. EA, arterial elastance; EV, ventricular elastance; LVEF, left ventricular function (%); PEP, preejection period; TSP, total systolic period; VTIAo, integrated time velocity of transaortic flow.

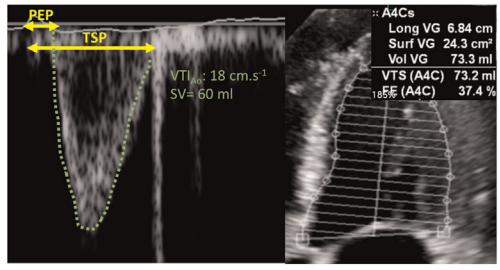
Panel A

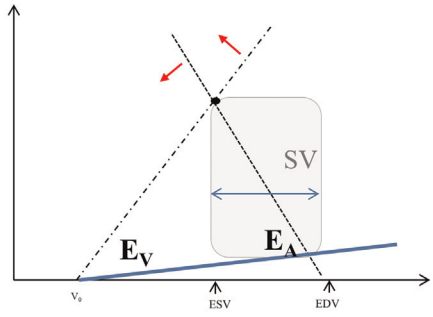




Heart rate : 73 bpm; Blood pressure: 123/58 mmHg
Norepinephrine 0.27 mcg kg^{-1} min^{-1}
Dobutamine 12.5 mcg kg^{-1} min^{-1}
E_A= 2.57 mm Hg ml^{-1}; E_V= 1.07 mm Hg ml^{-1}; E_A/E_V= 2.4

Panel B





Heart rate : 73 BPM; Blood pressure: 102/39 mmHg
Norepinephrine 0.15 mcg kg^{-1} min^{-1}
Dobutamine 12.5 mcg kg^{-1} min^{-1}
E_A= 1.53 mm Hg ml^{-1}; E_V= 1.25 mm Hg ml^{-1}; E_A/E_V= 1.23

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