Review

Myocardial fluid balance

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Summary

Fluid accumulation in the cardiac interstitium or myocardial edema is a common manifestation of many clinical states. Specifically, cardiac surgery includes various interventions and pathophysiological conditions that cause or worsen myocardial edema including cardiopulmonary bypass and cardioplegic arrest. Myocardial edema should be a concern for clinicians as it has been demonstrated to produce cardiac dysfunction. This article will briefly discuss the factors governing myocardial fluid balance and review the evidence of myocardial edema in various pathological conditions. In particular, myocardial microvascular, interstitial, and lymphatic interactions relevant to the field of cardiac surgery will be emphasized.

Keywords: Myocardial edema; Lymphatic system; Starling forces; Fluid balance; Cardiac function; Cardiac surgery; Cardioplegia; Contractility

1. Introduction

Fluid accumulation in the cardiac interstitium or myocardial edema has been documented in many disease states and its negative impact on cardiac function implied. Specifically, cardiac surgery includes many interventions and pathophysiological conditions that cause or worsen myocardial edema including cardiopulmonary bypass (CPB) and cardioplegic arrest. As reliable means to detect myocardial edema in the clinical setting are not readily available at the bedside, many clinicians do not include this entity in their differential diagnosis of cardiac dysfunction. Knowledge of the factors involved in myocardial fluid homeostasis may help to develop techniques minimizing myocardial edema formation and may lead to better therapeutic interventions. The purpose of this review is to provide an overview of myocardial fluid balance principles and discuss the conditions that are associated with water accumulation in the myocardium.

2. Pathophysiological effects of myocardial edema

Several pathophysiological consequences of myocardial edema have been described such as impairment of systolic function. The relation between preload recruitable stroke work, a contractility index independent of pre- and afterload [1], and myocardial edema experimentally induced by pulmonary artery hypertension [2] or coronary sinus pressure elevation [3] as well as CPB and cold crystalloid cardioplegia [4], warm continuous blood cardioplegia [5] or \( \beta \)-blockade [6] is depicted in Fig. 1. Similarly, Laine and Allen [7] demonstrated a decrease in cardiac output by 40\% for a given preload when myocardial water content was increased by 3.5\%. Myocardial edema has also been shown to impair diastolic cardiac function. Diastolic function consists of two phases: active, energy-consuming isovolumic relaxation and passive relaxation mainly determined by chamber stiffness [8,9]. Several investigators have demonstrated that myocardial edema impairs isovolumic relaxation by increasing \( \tau \), the time constant of the rate of isovolumic LV relaxation [2,3,10]. Studies have also shown that cardiac chamber stiffness increases with edema accumulation [10–12]. However, the mechanisms by which myocardial edema impairs cardiac function are poorly understood. One consequence of increased myocardial stiffness due to excess water is decreased ventricular compliance [11,13,14]. The impaired compliance in combination with the viscous effects of moving accumulated water could compromise cardiac efficiency. This is in agreement with data demonstrating increased cardiac energy requirements associated with edema [15]. In addition, the presence of edema expands the myocardial interstitium, possibly lead-
ing to myocyte ischemia by impeding coronary perfusion and increasing the diffusion distances for oxygen [16]. This is supported by work that demonstrated increased coronary vascular resistance associated with myocardial edema [13]. Further, myocardial edema may present technical problems in the operating room: Furnary et al. [17] reported that 18 of their 107 cases of delayed sternotomy were due to massively edematous hearts. Finally, myocardial edema may act as a trigger for interstitial cardiac fibrosis [7,18]. Davis et al. [19] recently demonstrated in a rat model that chronic myocardial edema was accompanied by increased mRNA levels of collagen types I and III as well as prolyl 4-hydroxylase, resulting in increased LV collagen deposition.

3. Principles of myocardial fluid balance

Myocardial fluid homeostasis is regulated by fluid filtration out of the microvascular exchange vessels into the cardiac interstitium and its removal from the interstitium via myocardial lymphatics [7,20]. Under normal conditions, the rate at which fluid enters the cardiac interstitium (JV) is equal to myocardial lymph flow rate (QL) and thus, myocardial water content remains constant [20,21]. Fig. 2 depicts the interactions that determine myocardial fluid balance.
4. Myocardial microvascular fluid filtration: Starling-forces

The forces that govern fluid flux out of the coronary microvasculature and into the interstitium can be summarized by the Starling equation [21,22]:

\[ J_V = L_m \times A \times [(P_c - P_m) - \sigma \times (\pi_c - \pi_m)] \]

where \( J_V \) is the rate at which fluid leaves the microvasculature (in ml min\(^{-1}\) g\(^{-1}\)), \( L_m \) is the myocardial microvascular hydraulic conductivity (in ml min\(^{-1}\) mmHg\(^{-1}\) cm\(^{-2}\)), \( A \) is the microvascular exchange vessel surface area (in cm\(^2\) g\(^{-1}\)), \( P_c \) is the hydrostatic microvascular exchange vessel ('capillary') pressure at end-diastole, \( P_m \) is the hydrostatic interstitial pressure at end-diastole, \( \sigma \) is the protein reflection coefficient or protein permeability, \( \pi_c \) is the plasma colloidal osmotic pressure, and \( \pi_m \) is the interstitial colloidal osmotic pressure (all pressures in mmHg).

\( P_c \) is the single most important factor governing the rate at which fluid enters the cardiac interstitium. \( P_c \) is difficult to determine in the heart, even in experimental manipulations. As microvascular exchange in the myocardium is probably present mostly on the venular side of the capillary bed [23], investigators have used the average of coronary sinus wedge pressure and coronary sinus pressure as an estimate of \( P_c \) [24]. Alternatively, \( P_c \) has been estimated by determining both coronary venular cross sectional area and blood flow under direct visualization [25]. Both techniques result in similar end-diastolic \( P_c \)’s of about 20–30 mmHg.

The interstitial tissue hydrostatic pressure (\( P_{int} \)) opposes \( P_c \) to inhibit fluid flux. In contrast to other tissues, this pressure fluctuates dramatically with each heart beat with \( P_{int} \) approaching arterial pressure during systole [20]. Thus, in the myocardium fluid exchange probably only occurs during diastole. Under normal conditions, \( P_{int} \) is about 15 mmHg during diastole [20,26].

The reflection coefficient, \( \sigma \), is a measure of the microvasculature’s ability to sieve proteins. It describes the fraction of protein molecules that are ‘reflected’ away from the microvascular membrane and can range from 0 (high permeability) to 1.0 (impermeable) [21]. In tissues that are relatively impermeable to proteins (or close to 1.0), the full effect of the colloidal osmotic pressure gradient (\( \pi_c - \pi_m \)) is active to oppose fluid flux [21,27,28]. Measurement of the reflection coefficient to albumin in many organs is made utilizing a wash-down technique. However, because of the magnitude of myocardial fluid flux, application of this technique in the heart is limited [20,29].

In normal myocardium absent of permeability disturbances, \( \sigma \) has been estimated to be in the range from 0.51 to 0.67 for total plasma protein and from 0.41 to 0.59 for albumin [20,29,30].

Plasma colloidal osmotic pressure, \( \pi_c \), represents the osmotic force generated by the plasma proteins (molecular weight >30,000 Da) that do not easily pass through the capillary membrane. \( \pi_c \) is the major force that opposes \( P_c \). Thus, simply a decrease in \( \pi_c \) such as that induced by hemodilution or crystalloid cardioplegia, increases fluid flux out of the capillaries (\( J_V \)) and may enhance edema formation. Direct measurement of \( \pi_c \) involves the use of an artificial membrane of arbitrary pore sizes while the capillary membrane probably consists of pores of various sizes. As the artificial membrane does not exactly reproduce the capillary membrane, many investigators measure the protein concentration and calculate \( \pi_c \) from derived equations [31,32]. Normal \( \pi_c \) is 21–24 mmHg in man and 17–19 mmHg in dogs [20,32,33].

Interstitial colloidal osmotic pressure, \( \pi_{int} \), cannot be directly measured but is thought to be similar to that measured in lymph. Normal \( \pi_{int} \) is 14 mmHg in the dog which results in a colloid osmotic gradient across the coronary microvascular of only 3–5 mmHg [20,33]. Data for \( \pi_{int} \) in man have not been published.

\( L_m \times A \) is the microvascular hydraulic conductivity – surface area product, commonly known as the filtration coefficient \( K_f \) or water permeability. Compared to other organs, capillary density in myocardium is high (3 \( \times \) 10\(^3 \) capillaries per mm\(^2 \) cross section) [23,34]. As a result, cardiac exchange surface area is about 500 cm\(^2 \) g\(^{-1}\) compared to only 70 cm\(^2 \) g\(^{-1}\) in skeletal muscle [35,36]. In addition, effective microvascular pore size is larger in myocardium (7–10 \( \mu \)m) [37–39] than in skeletal muscle (4–5 \( \mu \)m) [39] or gastrointestinal tract (5–6 \( \mu \)m) [40]. This produces a large \( K_f \) and results in a fluid flux that is at least 10 times greater on a per gram basis than in other tissues such as lung or skeletal muscle [41,42]. \( K_f \) is difficult to measure in the heart but has been estimated to be about 0.35 ml min\(^{-1}\) mmHg\(^{-1}\) 100 g\(^{-1}\) [34,36]. Assuming a capillary surface area of 500 cm\(^2 \) g\(^{-1}\), \( L_m \) can be estimated to be 7 \( \times \) 10\(^{-6} \) ml min\(^{-1}\) mmHg\(^{-1}\) cm\(^{-2}\).

5. Myocardial lymphatics

The mammalian heart is abundantly supplied with a network of lymphatic capillaries which drain myocardial interstitial fluid from the subendocardium to the subepicardium via intramyocardial channels [43]. Fig. 3 shows initial lymphatic capillaries in human LV myocardium detected by immunostaining against FLT-4, a class III tyrosine kinase receptor specific for lymphatic vessels. The subepicardial plexus drains into the subepicardial collecting trunks forming left and right coronary lymphatics which, eventually, terminate in the ‘principal’ cardiac lymphatic. The ‘principal’ cardiac lymphatic reaches the cardiac lymph node located in the connective tissue between the innominate artery and superior vena cava. Lymph collected for studies of the myocardial interstitium or lymphatics should be collected prenodally to eliminate changes which occur when lymph passes through a node [44]. However, Geissler et al. [45] recently studied the lymphatic anatomy in dogs and demonstrated that even prenodal cardiac lymph may contain pulmonary contamination. In contrast, Vasquez-
6. Myocardial edema and anti edema safety factors

Fluid accumulates in the cardiac interstitium if filtration rate \( J_f \) exceeds myocardial lymph flow rate \( Q_L \) \([20–22, 27–29]\). Thus, increased fluid filtration and reduced lymph flow rate each favor myocardial edema formation \([7,29]\). Inspection of the Starling equation reveals that increased filtration will occur if \( P_c \) increases or \( \pi_e \) decreases. Increased filtration will also occur if \( \sigma \) decreases or \( K_F \) increases. However, anti edema safety factors act to prevent the accumulation of fluid when filtration is increased \([18,29]\). Perhaps the most important safety factor is increased lymph flow \([29,53]\). Myocardial lymph flow increases mainly due to two mechanisms: increased lymph driving pressure and decreased lymphatic resistance \([18,29]\). Lymph driving pressure increases due to increased interstitial pressure \( P_{int} \) in response to increased filtration \([18,29,54]\). This is accompanied by a decrease in myocardial lymphatic resistance \([29]\) (Fig. 4). Another mechanism against edema formation is interstitial protein wash-down. Stewart et al. \([55]\) showed that myocardial interstitial protein concentration decreases in response to increased fluid filtration which tends to oppose edema formation by increasing the colloid osmotic pressure gradient \( (\pi_e - \pi_{int}) \) across the microvascular exchange barrier.

Edema formation is also enhanced if lymph flow is compromised. For example, occlusion of the cardiac lymphatics produces myocardial edema within hours of such a degree that coronary capillary compression occurs \([56]\). More commonly, lymph flow is impaired by any clinical disease state in which central venous pressure is increased. This is because myocardial lymphatics ultimately drain into the central venous circulation \([57]\). Thus, superior vena caval pressure represents the outflow pressure against which the lymphatics from the heart must pump and any lymphatic blockage or increase in central venous pressure can result in excess fluid accumulation within the myocardial interstitium \([2,7]\).

7. Cardiopulmonary bypass and cardioplegic arrest

Cardiopulmonary bypass (CPB) and cardioplegia enhance myocardial edema formation due to the combina-
tion of increased fluid filtration and decreased lymph flow. The increased filtration \( J_f \) can be explained according to the Starling equation:

1. Crystalloid priming-induced hemodilution used in clinical CPB practice reduces \( p_c \) [4–6,58]. Foglia et al. [59] showed that crystallloid CPB priming resulted in myocardial edema and cardiac dysfunction even in the absence of cardioplegic arrest. Infusion of crystallloid cardioplegia reduces \( p_c \) further to 0 mmHg [4,5].

2. Coronary perfusion and microvascular filtration are maximum during diastole [20]. As the heart remains in diastole during cardioplegia infusion, the entire ‘cardiac cycle’ is available for filtration in the absence of systole, thereby increasing the time-dependent \( L_m \). Assuming systole represents about one third of the cardiac cycle, \( L_m \) in the plegic heart is about 1.5 fold that of the normal beating heart [5,33].

3. CPB activates multiple humoral and cellular mediators, thus increasing microvascular permeability by increasing \( K_f \) and decreasing \( \sigma \) [60–62].

The other important mechanism that contributes to edema formation is reduced myocardial lymph flow during cardioplegia. As pointed out above, cardiac contraction is the major determinant of myocardial lymphatic function. In the absence of contraction during cardioplegia, lymph flow has been shown to almost cease [4]. Even during normothermic continuous antegrade blood cardioplegia lymph flow was below 20% of that in the normal beating heart [5]. These data suggest that impairment of myocardial lymphatic function contributes to edema during cardioplegia. Consequently, the most promising strategy to minimize myocardial edema during CPB and cardioplegia is to reduce fluid filtration by either decreasing \( P_c \) or increasing \( p_c \). \( P_c \) depends mainly on the perfusion pressure [21,27]. Buckberg et al. [63] noticed rapid myocardial edema formation at a cardioplegia perfusion pressure of 100 mmHg, and thus suggested a limit of 50 mmHg. However, several investigators found that even cardioplegia perfusion pressures of 40–60 mmHg do not prevent myocardial edema [5,12,64]. Reduction below 40 mmHg would probably further reduce \( J_f \) and thus edema, but would most likely cause (subendocardial) ischemia, and thus, abolish the benefits of edema prevention [65,66].

Alternatively, \( p_c \) elevation reduces fluid filtration. Laks et al. [58] demonstrated that iso-oncotic hemodilution using plasma resulted in minimal myocardial water gain after 1 h of CPB, whereas crystallloid hemodilution using Ring-er’s lactate caused significant myocardial edema. However, in the arrested heart, addition of osmotic or oncotic active substances such as mannitol or albumin did not reduce fluid filtration to a rate sufficient to prevent edema [12,67]. Lindbergh et al. [68] added dextran to crystallloid cardioplegia and found that these patients had slightly better postoperative oxygen consumption and faster chest X-ray normalization as compared to crystallloid cardioplegia only. In an experimental study, investigators estimated that hyperoncotic normothermic continuous blood cardioplegia delivered at 50 mmHg perfusion pressure would require a colloid oncotic pressure (\( p_c \)) of about 36 mmHg to stop myocardial microvascular fluid filtration, and thus subsequent edema formation [33].

Other experimental pharmacological interventions aimed at minimizing myocardial edema associated with cardioplegic arrest include addition of 2,3-butanedione monoxime (BDM) [69], diazoxide, an ATP-sensitive potassium channel opener [70], or sodium/hydrogen exchanger inhibitors such as HOE-642 [71] to the cardioplegia composition. Even though addition of these substances has been shown to be associated with less edema formation as compared to controls [69–71], the mechanisms by which this is achieved are not fully understood. One potential mechanism is improved postischemic intracellular Ca\(^{2+}\)-handling resulting in better preserved contractility which, in turn, hastens edema resolution as has been demonstrated [50].

An alternative approach to minimize edema formation is to support myocardial lymphatic function during CPB. Our group has investigated a technique consisting of continuous coronary perfusion with normothermic oxygenated blood enriched with the ultra short-acting \( \beta \)-blocker esmolol on CPB [6,72–74]. We showed that the modest degree of cardiac contraction that still persisted during \( \beta \)-blockade was sufficient to maintain myocardial lymph flow, resulting in only minimal myocardial edema associated with normal cardiac performance post CPB [6]. These experimental data have recently been confirmed in clinical studies demonstrat-
Michael et al. [84] showed that increased myocardial permeability, potentially leading to edema formation.

9. Myocardial ischemia/infarction
Myocardial ischemia increases myocardial microvascular permeability, potentially leading to edema formation. Michael et al. [84] showed that 15 μm microspheres were able to pass from the systemic circulation into the cardiac lymphatics after only 20 min of ischemia. However, the edema associated with this increased permeability does not appear to affect myocardial blood flow. Carlson et al. [85] administered mannitol in an ischemia-reperfusion model and despite demonstrating a decrease in water content, they neither found a change in myocardial blood flow nor wall motion abnormalities. Other investigators have shown that hyperosmotic reperfusion of ischemic myocardium not only resulted in myocardial edema resolution but also infarct size reduction [86]. Although not conclusive, these data suggest that attenuating edema formation may limit infarct size perhaps by shortening the diffusion distance for oxygen [16]. In patients with acute myocardial infarction, hyaluronidase infusion has been shown to reduce infarction size [87]. Hyaluronidase increases myocardial lymph flow rate presumably by reducing the resistance to fluid flow in the interstitium; thus, the increased flow through the interstitium could potentially enhance the wash-out of metabolites which act as mediators of reperfusion injury.

During reperfusion following ischemia, myocardial microvascular filtration (fL) is probably enhanced due to exchange vessel permeability increase (decrease in σ) secondary to endothelial injury [88]. However, microvascular permeability increase does not necessarily result in myocardial edema formation [61]. As myocardial lymph flow can increase several fold in response to increased filtration [29,30,33], excess water will only accumulate in the myocardium if this anti-edema safety mechanism is exhausted.

10. Arterial hypertension
Increased cardiac afterload such as in arterial hypertension or aortic valve stenosis is known to cause LV hypertrophy, but its effects on myocardial fluid homeostasis are less well defined. Interestingly, patients with hypertension had worse clinical outcome after acute myocardial infarction compared with normotensive patients [89]. Our group [29] has shown that hypertensive arterial pressures are transmitted to the myocardial microvascular exchange vessels leading to increased fluid filtration, subsequent myocardial lymph flow increase, and interstitial protein wash-down. However, in this acute study increased fluid turnover in the cardiac interstitium was not associated with myocardial edema because increased lymph flow compensated for increased filtration [29]. In contrast, chronic arterial hypertension has been shown to be associated with elevated microvascular permeability to both water (Kw) and protein (σ), leading to myocardial edema formation [90]. Thus, alterations in the protein and fluid composition of the cardiac interstitium could precede and/or influence LV hypertrophy in systemic hypertension.

11. Pulmonary hypertension
Left ventricular dysfunction has been associated with pulmonary hypertension [91]. Recent studies have established that both acute and chronic pulmonary hypertension are associated with fluid accumulation in the LV myocardium and LV dysfunction [2,7,19]. In pulmonary hypertension, LV edema occurs due to the following mechanisms. Pulmonary hypertension increases right heart pressure and, subsequently, central venous pressure. As myocardial lymph ultimately drains into the central venous system via the thoracic duct [18,43], central venous pressure elevation impedes fluid removal from the cardiac interstitium via myocardial lymphatics [2,7,19]. In addition, increased central venous pressure increases coronary sinus pressure, and thus, coronary microvascular pressure (Pc) which enhances fluid filtration out of the coronary microvascula-
ture into the cardiac interstitium [2,3,7]. Both factors act in concert leading to LV myocardial edema formation associated with LV dysfunction [2,3,7,19]. Moreover, chronic LV edema secondary to pulmonary hypertension has been shown to be accompanied by increased collagen types I and III and prolyl 4-hydroxylase mRNA levels as well as decreased collagenase activity, resulting in increased LV collagen deposition [19]. This suggests that chronic myocardial edema acts as a trigger for LV fibrosis contributing to the LV dysfunction seen in pulmonary hypertension.

12. Implications for Fontan-type circulation

Following Fontan-type operations, central venous pressure and thus, coronary sinus pressure sometimes rises substantially above 15 mmHg and is associated with LV dysfunction [92,93]. Ilbawi et al. [94] compared the results of experimental coronary sinus pressure elevation and their clinical data. They found that left ventricular dysfunction was related to the degree of coronary sinus hypertension and surmised that myocardial edema was a factor [94]. Pratt et al. [3] recently demonstrated that only 3 h of coronary sinus pressure elevation to 25 mmHg resulted in myocardial edema associated with decreased LV end-systolic elastance and preload recruitable stroke work as well as prolonged time constant of LV relaxation. These data support the previous discussion of the impact of increased venous pressure on myocardial fluid balance and suggest that diverting the coronary sinus to the left atrium during Fontan-type operations is desirable in view of myocardial fluid balance principles.

13. Sepsis

Cardiac dysfunction has been documented in both experimental and clinical sepsis [95]. As microvascular permeability is frequently increased in sepsis, myocardial edema is a likely contributor to impaired cardiac performance. Goddard et al. [96] demonstrated that myocardial leukocyte infiltration and interstitial edema accompanied compromised ventricular contractility in experimental sepsis. Yu et al. [97] reported myocardial edema and decreased cardiac collagen content; they concluded that these changes may contribute to cardiac dysfunction and LV dilatation observed in sepsis. Gotloib et al. [98] showed that sepsis-induced myocardial edema was associated with a loss of the normal amount of negatively charged large molecules that are thought to form part of the microvascular exchange barrier. Edema resolved concomitantly with recovery of the negative charges [98]. These data suggest that increased permeability and subsequent edema may occur in sepsis secondary to leukocyte-mediated endothelial injury, resulting in removal of the ionic permeability regulators.

14. Detection of myocardial edema

In experimental studies, myocardial edema is usually quantified using gravimetric (wet to dry) methods [2,3,7,19,20]. However, conventional gravimetric methods require too large a sample for sequential determinations. Recently, a microgravimetric technique originally developed for cerebral edema measurement has been modified for myocardial water content quantification [5]. With this technique, myocardial water content is determined by specific density measurement of small myocardial samples of about 5 mm³ using a linear density gradient. Knowing the specific density of a myocardial sample, the percent gram water per gram tissue can be calculated [5]. This technique allows time course measurement of both myocardial edema formation and resolution [5,6,72,73]. However, due to its invasive nature, clinical use of this technique is limited to open cardiac surgery [75]. As an interesting alternative, Albers et al. [9] recently investigated the distribution of crystalloid cardioplegia-induced myocardial edema using 3D-reconstructed MRI. They found myocardial water content increases of 4–6% in all regions of both ventricles with particular water gain in LV posterior and lateral wall [99].

The clinical diagnosis of myocardial edema is difficult because of the lack of a readily available method. Computer tomography has been suggested to be a potential means for sequential non-invasive quantification of myocardial edema [100]. Several investigators have shown that MRI can detect myocardial edema due to either myocarditis or myocardial ischemia by simply adjusting the technique of image acquisition [101,102]. MRI is particularly suited for edema detection as it images protons of which water has a higher density measurement of both myocardial edema formation and resolution [5,6,72,73]. However, due to its invasive nature, clinical use of this technique is limited to open cardiac surgery [75]. As an interesting alternative, Albers et al. [9] recently investigated the distribution of crystalloid cardioplegia-induced myocardial edema using 3D-reconstructed MRI. They found myocardial water content increases of 4–6% in all regions of both ventricles with particular water gain in LV posterior and lateral wall [99].

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Echocardiography has been used for edema quantification in animal and human studies [76,105,106]. However, for broad clinical application further improvements in image resolution and processing are necessary. Clinically significant myocardial edema results in a 10% increase in ventricular wall thickness. As adult ventricular wall thickness is about 10–12 mm [107], echocardiography would have to reliably detect 1 mm changes.

15. Conclusion

Myocardial edema is an often overlooked entity in both the cardiac surgical and the critically ill medical patient with compromised cardiac function. This is compounded by the
degree of presumption required for the diagnosis. Our knowledge about myocardial fluid balance under normal and numerous pathological conditions has been gathered over the past 60 years. Fig. 5 depicts the various factors that enhance myocardial dysfunction due to edema. Awareness of the forces which regulate fluid filtration and removal as well as the impact of various insults on microvascular permeability should improve clinical awareness of this condition. However, further investigation is required to improve techniques for clinical myocardial edema quantification and to generate new strategies for optimized patient care.

References


[8] Brutsaert DL, Sys SU, Gillibert TC. Diastolic failure: pathophysiol-


