Pharmacology & Therapeutics 139 (2013) 32–40

Contents lists available at SciVerse ScienceDirect

Pharmacology & Therapeutics

journal homepage: www.elsevier.com/locate/pharmthera

Matrix metalloproteinase (MMP)-9: A proximal biomarker for cardiac remodeling and a distal biomarker for inflammation

Ganesh V. Halade [a,b,c], Yu-Fang Jin [a,d], Merry L. Lindsey [a,e,f,*]

[a] San Antonio Cardiovascular Proteomics Center, The University of Texas Health Science Center at San Antonio, United States
[b] Barshop Institute for Longevity and Aging Studies, The University of Texas Health Science Center at San Antonio, United States
[c] Division of Geriatrics, Gerontology and Palliative Medicine, Department of Medicine, The University of Texas Health Science Center at San Antonio, United States
[d] Department of Electrical and Computer Engineering, University of Texas at San Antonio, United States
[e] Jackson Center for Heart Research, Department of Physiology and Biophysics, University of Mississippi Medical Center, United States
[f] Research Service, G.V. (Sonny) Montgomery Veterans Affairs Medical Center, United States

ARTICLE INFO

Keywords:
Biomarker
Cardiovascular
Congestive heart failure
Inflammation
MMP-9
Myocardial infarction

ABSTRACT

Adverse cardiac remodeling following myocardial infarction (MI) remains a significant cause of congestive heart failure. Additional and novel strategies that improve our ability to predict, diagnose, or treat remodeling are needed. Numerous groups have explored single and multiple biomarker strategies to identify diagnostic prognosticators of remodeling progression, which will improve our ability to promptly and accurately identify high-risk individuals. The identification of better clinical indicators should further lead to more effective prediction and timely treatment. Matrix metalloproteinase (MMP-9) is one potential biomarker for cardiac remodeling, as demonstrated by both animal models and clinical studies. In animal MI models, MMP-9 expression significantly increases and is linked with inflammation, diabetic microvascular complications, extracellular matrix degradation and synthesis, and cardiac dysfunction. Clinical studies have also established a relationship between MMP-9 and post-MI remodeling and mortality, making MMP-9 a viable candidate to add to the multiple biomarker list. By definition, a proximal biomarker shows a close relationship with its target disease, whereas a distal biomarker exhibits non-targeted disease modifying outcomes. In this review, we explore the ability of MMP-9 to serve as a proximal biomarker for cardiac remodeling and a distal biomarker for inflammation. We summarize the current molecular basis and clinical platform that allow us to include MMP-9 as a biomarker in both categories.

Contents

1. Introduction

Despite significant advancements in risk prediction, cardiovascular disease remains a leading cause of death (Roger et al., 2011). Myocardial infarction (MI) is one of the most highly prevalent cardiovascular diseases, with over 1.2 million Americans being diagnosed with MI annually. While short-term one month survival rates have dramatically improved over the last 30 years, post-MI remodeling progressing to heart failure remains a significant clinical issue. This issue is further fueled by increased incidences of obesity, metabolic syndrome, and diabetes, all of which exacerbate the cardiac remodeling response (Horwich & Fonarow, 2010; Roger et al., 2011). Because heart failure is associated

* Corresponding author at: Department of Physiology and Biophysics, University of Mississippi Medical Center, 2500 North State Street, Room G351-04, Jackson, MS 39216-4505, United States. Tel.: 601 815 1329; fax: +601 984 1817.
E-mail address: mllindsey@umc.edu (M.L. Lindsey).

0163-7258
http://dx.doi.org/10.1016/j.pharmthera.2013.03.009

with substantial morbidity and mortality, as well as an impaired quality of life (Goldberg et al., 2007), improved methods to identify at risk patients before they develop heart failure is a primary goal. MI modulates several biological pathways that converge in the remodeling response, which is characterized by changes in left ventricle (LV) size, shape, and function (Lindsey & Zamilpa, 2012; Pfeffer & Braunwald, 1990).

Several plasma or serum proteins have been characterized in the context of heart failure, and these are broadly classified as markers of LV remodeling. Included in the list are extracellular matrix (ECM) markers — collagen, matrix metalloproteinases (MMPs), and tissue inhibitors of metalloproteinases (TIMPs); inflammatory markers — C-reactive protein (CRP), tumor necrosis factor α, and interleukins (IL) — 1, 6, and 18; oxidative stress markers — homocysteine and myeloperoxidase; neurohormonal activation markers — renin, angiotensin II, and aldosterone; myocyte injury markers — cardiac specific troponins and creatine kinase; and myocyte stress markers — brain natriuretic peptide (BNP) and N-terminal pro-BNP (Braunwald, 2008; Fertin et al., 2012; Maisel et al., 2002; Opdenakker et al., 2001; Tang et al., 2007; Velagaleti et al., 2010). To date, a myriad of candidate circulating biomarkers have been examined as LV remodeling or heart failure predictors, but the use of one biomarker to accurately assess disease diagnosis, stage, and progression has not been successful and is not expected to be fruitful. To illustrate this point, while average BNP levels are higher in patients with heart failure, individual levels vary from 100 to 1400 ng/ml. BNP shows a wide spectrum of values and does not stratify with heart failure stage, and BNP responses to heart failure treatments are influenced by comorbidities such as renal failure (Lang & Mancini, 2007). This variation is so large that BNP cannot effectively separate patients with and without heart failure (Maisel et al., 2002). A more successful approach will likely be to use a multi-marker panel profiling scheme to assess markers during each category (diagnosis, stage, progression) from the initial MI event to progressive remodeling to the development of heart failure. Of the analytes that have been examined, MMPs provide several candidate biomarkers.

MMPs are zinc-dependent endopeptidases that cleave several ECM proteins and as such modulate outcome of various physiological and pathological processes including MI, atherosclerosis and congestive heart failure. In addition to structural ECM components, MMP substrates also include a multitude of ligand and receptor substrates such as cytokines, chemokines, growth factors, and adhesion molecules that alter cellular migration, adhesion, and activation. MMPs, therefore, exert a strong influence on cardiac remodeling through multiple mechanisms (Lindsey, 2004; Lindsey & Zamilpa, 2012; Sternlicht & Werb, 2001). MMPs are endogenously inhibited by the tissue inhibitors of metalloproteinases (TIMPs), a family comprised of four members, TIMP-1, -2, -3, and -4. Pre-clinical and clinical studies in the post-MI setting indicate that MMP-1, -2, -3, -7, -8, -9, -12, -13, and -14 and TIMP-1, -2 -3, and -4 are relevant to MI and LV remodeling (Hansson et al., 2011; Lindsey & Zamilpa, 2012; Rohde et al., 1999; Yarbrough et al., 2003; Zamilpa & Lindsey, 2010).

For the most part, MMPs are secreted from the cell as proMMPs and are activated extracellularly by tissue or plasma proteinases. The first step in activation involves cleavage of a part of the propeptide, and complete activation occurs with removal of the entire propeptide by the MMP intermediate or by other active MMPs (Nagase et al., 2006). MMPs can also be activated in vitro by treatment with organomercurial compounds, urea, SH reagents, and chaotropic agents, which chemically perturb the proMMP to alter its structure and permit activity without loss of the 10 kD pro-domain. Other exogenous MMP activators include oxidants such as HOCl and $ONOO^-$, which activate proMMPs by reacting with the cysteine in the propeptide. This activation process can also take place in vivo, under inflammatory conditions (Gu et al., 2002; Peppin & Weiss, 1986). On the other hand the major endogenous MMP inhibitor in serum is α2-macroglobulin and in tissue are the TIMPs (Sorokin, 2010).

In 2001, an NIH working group standardized the definition of a biomarker as any characteristic that can be objectively evaluated as an indicator of a normal biological process, a pathological process, or a pharmacological responses to therapeutic intervention (Biomarkers Definitions Working Group, 2001; Vasan, 2006). The American Heart Association released a scientific statement focused on the importance for developing biomarkers to enhance diagnostic methods and provide surrogate measures of treatment efficacy (Balagopal et al., 2011; Fortmann et al., 2004; Hlatky et al., 2009; Richards, 2009; Smith et al., 2004; Vasan, 2006). Because no single biomarker will likely provide sufficient information to predict disease progression, the next step is to identify the combination of markers that improve risk prediction beyond what is currently available. A combination biomarker strategy can also be used strategically to make go or no-go decisions that will accelerate drug discovery (Krishna & Wagner, 2010). An essential biomarker, by definition, would modulate both the target response as well as distal events related to disease outcome (Krishna & Wagner, 2010; Krishna et al., 2008).

In this review, we provide rationale for using MMP-9 as a biomarker. We will discuss its effectiveness as a proximal biomarker for cardiac remodeling (one that shows a close relationship with its target disease) and a distal biomarker for inflammation (one that exhibits non-targeted disease modifying outcomes). We provide a logic model by which to evaluate the inclusion of MMP-9 as a candidate marker for post-MI remodeling that may also serve as a template to evaluate other candidate markers.

2. Methods of review

We searched PubMed for all papers that included MMP-9, which totaled over 13,000 papers. We then focused the search by articles published in the past 1, 2, 3, 5, or 10 years. Subsequently, we added inflammation, cardiac remodeling, cardiovascular, myocyte, fibroblast, neutrophils, or leukocytes to the MMP-9 keyword search (each term was searched individually with MMP-9). We included all clinical reports, review articles, journal articles, clinical trial reports, meta-analysis studies, randomized controlled trials, and original research manuscripts that were published in English. The numbers of manuscripts with these key words are shown in Fig. 1.

3. Pre-clinical and clinical studies: MMP-9-mediated proximal effects (Fig. 2)

3.1. Post-MI LV healing phases

Following MI, both the infarcted region as well as the remote non-infarcted zone undergo cardiac remodeling as a part of the wound healing response (Pfeffer & Braunwald, 1990). The LV healing response can be divided into two overlapping phases, the inflammatory and reparative phases. The first phase, the inflammatory phase, is characterized by the robust release of inflammatory mediators and degradation of ECM that occurs in the setting of myocyte necrosis. During the inflammatory phase, cardiomyocyte death triggers the rapid activation of the complement system, which induces free radical production and activates the toll-like receptor-mediated pathway. The second phase, the reparative phase, is characterized by fibroblast proliferation and release of fibrosis-promoting cytokines that contribute positively to scar formation, with the net result being increased ECM synthesis and deposition (Frantz et al., 2009).

The inflammatory and fibrotic pathways share several components. For example, both pathways involve activation of nuclear factor kappa-B (NF-κB) in infiltrating and resident myocardial cells to stimulate the expression of cytokines, chemokines, growth factors, and adhesion molecules. Among these factors are IL-1β, tumor necrosis factor α, monocyte chemotactic protein (MCP)-1/(CCL2), and intercellular adhesion molecule 1, which stimulate and facilitate leukocyte intravasation into the

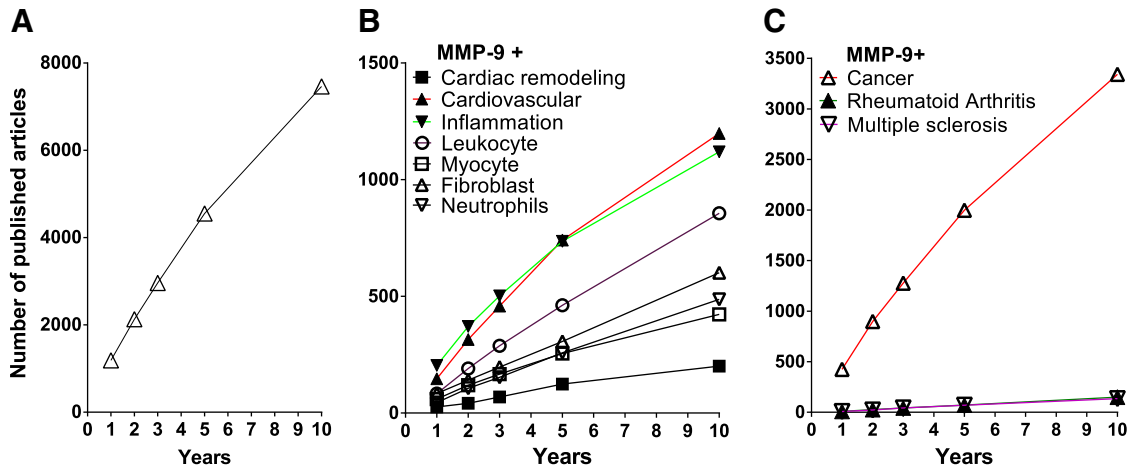


Fig. 1. Research articles and reviews on MMP-9 published in the last decade (2001–2010). **A**. Total number of articles on MMP-9 published. **B**. Number of articles published on MMP-9 and cardiovascular disease, including articles on the proximal effect on cardiac remodeling. **C**. Number of articles published on MMP-9 in other inflammatory diseases (cancer, arthritis, and multiple sclerosis).

infarct region. During permanent occlusion, neutrophil infiltration occurs primarily during days 1–3 post-MI, while macrophage infiltration occurs primarily during days 3–7 post-MI. During reperfusion, the kinetics and amplitude of the inflammatory response shifts, such that both neutrophils and macrophages enter the tissue simultaneously as soon as reperfusion is initiated. The transition from the inflammatory to reparative phase is associated with the activation of pathways that turns off inflammation and promotes ECM scar formation (Dobaczewski et al., 2010; Frantz et al., 2009). Targets involved in inflammatory events and reparative processes will be central components of a successful LV remodeling biomarker discovery and drug target development.

3.2. MMP-9 expression in post-MI cardiac remodeling

Table 1 highlights basic science studies evaluating LV MMP-9 levels in animal models, while Table 2 highlights clinical trials examining LV MMP-9 levels in humans. MMP-9 is expressed in cardiac myocytes, fibroblasts, vascular smooth muscle cells, endothelial cells, neutrophils, macrophages, and fibroblasts (Coker et al., 2001; Hasty et al., 1990; Heymans et al., 1999; Kawakami et al., 2004; Lindsey et al., 2001, 2006b; Opdenakker et al., 2001; Porter & Turner, 2009; van den Borne et al., 2009). MMP-9 was first described as being able to process only collagen that was first denatured or already cleaved by collagenases such as MMP-1. Recent literature, however, has shown that MMP-9 can process full length interstitial collagens (Egeblad & Werb, 2002; Lauer-Fields et al., 2008). Further, MMP-9 does not require an activation cleavage step to proteolyze substrates. Pro-MMP-9, in the presence of substrate, has enzymatic activity without the loss of the 10 kDa pro-domain (Bannikov et al., 2002).

MMP-9 activates several chemokines, including CXCL5, CXCL6, and CXCL8, and contributes to the release of cell surface receptors (e.g., tumor necrosis factor-α receptor) to alter the local microenvironment (Van Den Steen et al., 2003). MMP-9 also has several inflammatory response elements, including activator protein-1, specificity protein-1, and NF-κB sites that makes it highly responsive to inflammatory stimuli (Benbow & Brinckerhoff, 1997; Lindsey & Zamilpa, 2012). In the mouse, rat, pig, rabbit, and dog models of MI, MMP-9 levels are consistently

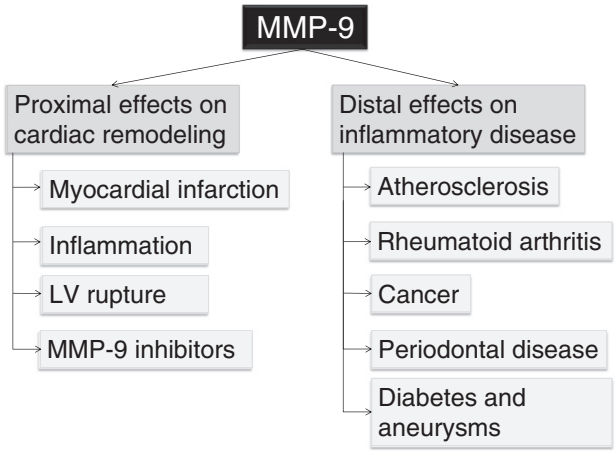


Fig. 2. The effect of MMP-9 is broadly classified into effects proximal and distal to cardiac remodeling. 1. Proximal effects targeted on cardiac remodeling and 2. Distal effects (non-targeted) on inflammatory diseases.

Table 1
Pre-clinical studies: A selection of articles to summarize the role of MMP-9 in cardiac remodeling.

Reference and year	Animal model	Sex	Significant findings
Heymans et al., 1999	MMP-9 null mice post-MI	Male	↓ cardiac rupture
Ducharme et al., 2000	MMP-9 null mice post-MI	Male	↓ collagen accumulation and macrophage infiltration ↓ LV dimension ↑ MMP-2, MMP-13, and TIMP-1
Romanic et al., 2001	Rabbit post-MI	Female	↑ MMP-9 within 24 h following MI
Lindsey et al., 2005	Aging CB6F1 mice	Both	↑ LV end-diastolic dimensions and wall thickness in middle aged and old mice. ↑ MMP-9 in old mice
Lindsey et al., 2005	MMP-9 null mice post-MI	Both	↑ neovascularization post-MI
Mukherjee et al., 2006	Gelatinase B/lacZ transgenic mice post-MI	Both	↑ MMP-9 promoter induction at day 3, peaks at day 7
Yan et al., 2006	C57BL/6J mice post-MI	Male	↑ LV rupture in middle aged mice ↑ LV remodeling and MMP-9 activity
Chiao et al., 2011	Aging C57/BL6J mice	Both	↑ MMP-9 and MCP-1 levels in plasma and LV ↑ macrophage density in LV with aging

increased in the infarct region (Ducharme et al., 2000; Etoh et al., 2001; Heymans et al., 1999; Lindsey et al., 2001, 2005, 2006a; Romanic et al., 2001; Tao et al., 2004). In mouse, rabbit, and pig MI models, pharmacological MMP inhibition reduces LV dilation and preserves cardiac function (Chancey et al., 2002; Mukherjee et al., 2003; Rohde et al., 1999; Spinale et al., 1999). Mice with targeted deletion of the MMP-9 gene show attenuated LV dilation after experimental MI accompanied by decreased collagen accumulation (Ducharme et al., 2000; Heymans et al., 1999). Interestingly, however, MMP-9 deletion also stimulates neovascularization in the post-MI infarct region (Lindsey et al., 2006a). This suggests that MMP-9 serves both beneficial and detrimental roles in the post-MI response.

Table 2
Clinical studies: A selection of articles to summarize the role of MMP-9 in cardiac remodeling.

Reference and year	Patient population (n)	Location	Significant findings	Conclusion
Blankenberg et al., 2003	coronary artery disease (1127)[a]	Germany	MMP-9 higher at baseline in patients with a subsequent fatal CV event	MMP-9 as a novel predictor of future CV mortality
Squire et al., 2004	acute MI (60)[a]	UK	MMP-9 peaks at days 1–4 post-MI	MMP-9 present during LV remodeling
Sundstrom et al., 2004	previous MI but no heart failure (699)[a]	USA	Plasma MMP-9 linked to vascular risk factors and echocardiography measurements in males	MMP-9 levels associate with increased LV diastolic dimensions and increased wall thickness
Yan et al., 2006	symptomatic heart failure with reduced ejection fraction (184)[a]	Canada and USA	↑ MMP-9 levels correlate with increased LV volumes and reduced LV ejection fraction in patients with heart failure	MMP-9 levels associate with cardiac dysfunction
Hlatky et al., 2007	acute MI or stable angina (199)[a]	USA	↑ MMP-9 in acute MI but not stable angina patients	MMP-9 independently associates with development of an acute MI rather than stable angina
Martos et al., 2007	hypertensive with diastolic dysfunction (86)[a]	Ireland	↑ MMP-9 in diastolic heart failure	↑ MMP-9 levels associate with active fibrosis
Orn S et al., 2007	Long-term survivors after MI (52)[a]	UK and USA	↑ MMP-9 in the acute phase after MI, protective effect during late LV remodeling	No relationship between MMP-9 levels and scar size at any time point after MI
Van den Borne et al., 2009	Autopsy samples of post-MI ruptures (20)[b]	Netherlands	↑ MMP-9 in ruptured LVs	↑ MMP-9 in infarcted area associates with rupture
Hansson et al., 2011	Uppsala Longitudinal Study of Adult Men (ULSAM) (1082)[a]	Sweden	↑ MMP-9 and TIMP-1 in men with CV mortality	MMP-9 and TIMP-1 are related to CV mortality risk
Kobayashi et al., 2011	ST elevated ACS and non-ST elevated ACS stable angina patients (266)[a]	Japan	↑ MMP-9 early post-MI	MMP-9 has higher diagnostic accuracy for ACS than hs-troponin

Abbreviations: CV; cardiovascular, LV; left ventricle, ESV; end systolic volume, HF; heart failure, MI; myocardial infarction
[a] Indicates that MMP-9 was analyzed by ELISA.
[b] Indicates MMP-9 was analyzed by zymography or immunocapture activity.

A striking increase in MMP-9 activity is found at days 1 to 4 in the infarct region, and this increase corresponds with neutrophil and macrophage infiltration (Ducharme et al., 2000; Heymans et al., 1999; Hudson et al., 2006; Ramani et al., 2004; Tao et al., 2004). Mukherjee et al. demonstrated that MMP-9 promoter transcripts with a β-galactosidase reporter show MMP-9 promoter activity at day 3 post-MI that peaked at day 7 (Mukherjee et al., 2010). The earlier initial increase in MMP-9 protein levels seen at day 1 post-MI is due to the release of pre-formed MMP-9 from infiltrating neutrophils, where it is stored in gelatinase granules (Mukherjee et al., 2010).

Kelly and colleagues provided insight into the complexity of MMP-9 in terms of its having both beneficial and detrimental roles during post-MI remodeling (Kelly et al., 2007). They found that increased early levels of MMP-9 associated with both neutrophil numbers and the extent of LV remodeling, indicating that MMP-9 from the neutrophil has an overall detrimental effect. In contrast, increased late levels of MMP-9 associated with preservation of LV function, indicating that MMP-9 after the initial wound healing phase may serve an overall beneficial effect. The temporal profile of MMP-9, in addition to its magnitude, is an important consideration. Post-MI, the establishment of new blood vessel networks is needed to supply oxygen to the highly metabolically active infarct area (Sim et al., 2002). Of note, MMP-9 deletion enhanced neovascularization in the post-MI setting in mice, suggesting that targeted strategies to inhibit MMP-9 early post-MI might improve rather than impair angiogenesis (Lindsey et al., 2006a).

Recent advances in mass spectrometry-based proteomic approaches and new emerging technologies hold particular promise for unbiased discovery and subsequent validation of novel biomarkers of cardiovascular disease (Gerszten et al., 2011). As an example of such an approach, Zamilpa et al. identified multiple proteins that are differentially expressed in the infarct region of MMP-9 null mice compared to wild type mice. Among previously known in vitro MMP-9 substrates, fibronectin was validated as an in vivo MMP-9 substrate in the post-MI setting (Zamilpa et al., 2010).

3.3. MMP-9 effects on LV rupture

LV wall rupture is one of the more serious complications, accounting for 5 to 31% of all in-hospital MI deaths (Figueras et al., 2000). While rupture rates in humans have fallen due to the success of reperfusion, the incidence of LV ruptures remains at 0.5%–1.4% (Lopez-Sendon et al., 2010). LV ruptures are more frequent in patients with STEMI (0.9%) than patients with other acute coronary syndromes (NSTEMI, 0.17%; unstable angina, 0.25%) (Lopez-Sendon et al., 2010). In C57BL/6J male mice, the 7 day post-MI survival rate is approximately 60%, and about one in three deaths will occur as a result of rupture (Gao et al., 2005; Yang et al., 2008; Zamilpa et al., 2011). Survival in female mice is about 90% at day 7 post-MI, with about one in ten deaths occurring as a result of rupture. Gender studies in 129sv mice showed that males have higher MMP-9 activity in the infarct region associated with increased inflammatory cell infiltration, as well as increased MMP-9 expression in circulating peripheral blood mononuclear cells (Fang et al., 2010). MMP inhibition using the CP471, 474 inhibitor significantly reduced both rupture incidence and MMP-9 activity in mice, supporting a role of MMP-9 in the pathogenesis of rupture. In humans, increased MMP-9 levels have been detected in ruptured human ventricles (van den Bornes et al., 2009). LV ruptures in human and mice share an association between rupture rates and the accumulation of inflammatory cells, as well as a common location at the border zone. LV ruptures in human and mice are disparate in the influence of sex on rupture rates (Gao et al., 2005). In the clinical setting, the risk of post-MI rupture is higher in females than males (Figueras et al., 2000; Reardon et al., 1997).

3.4. Clinical studies: MMP-9 is a biomarker for cardiac remodeling

Blankenberg and colleagues performed the first comprehensive clinical study that implicated MMP-9 as a novel prognostic biomarker for individuals at increased risk for CV mortality (Blankenberg et al., 2003). MMP-9 correlated with the acute-phase reactant proteins IL-6, hs-CRP, and fibrinogen, indicating that MMP-9 could have its own pathophysiological significance in cardiovascular mortality. Squire and colleagues extended these studies to demonstrate that, in humans, higher MMP-9 correlated with larger LV volumes and greater dysfunction following MI (Squire et al., 2004). The Vasan team examined patients from the Framingham Heart Study and found that plasma MMP-9 levels associated with increased LV diastolic dimensions and increased wall thickness (Sundstrom et al., 2004). Hlakty and colleagues showed that circulating MMP-9 levels independently associated with acute MI but not stable angina (Hlatky et al., 2007). MMP-9 levels correlated with LV enlargement, lower ventricular ejection fraction, and persistent adverse LV remodeling in chronic systolic heart failure patients (Yan et al., 2006). Fertin et al. examined 112 correlations among 52 different biomarkers and LV remodeling indices. The most consistent biomarkers associated with LV remodeling were related to ECM turnover or neurohormonal activation. Among the biomarkers, MMP-9, collagen peptides, and B-type natriuretic peptide were prominent biomarkers that predicted adverse LV remodeling after MI (Fertin et al., 2012). Of note, several polymorphisms have been evaluated within the MMP-9 gene and have been shown to influence gene expression (B. Zhang et al., 1999). Specifically, the C1562T allele associates with increased MMP-9 plasma concentrations, whereas the R279Q polymorphism had no effect on plasma levels but associated with future CV events. The 279 amino acid where these polymorphisms occur resides in the catalytic domain of the MMP-9 enzyme, suggesting that MMP-9 activity levels may be higher in patients with the R279Q polymorphism (Shipley et al., 1996; Tanner et al., 2011). Combined, these studies offer strong evidence for a proximal role of MMP-9 in LV remodeling. In heart failure patients, serum carboxy-terminal telopeptide of procollagen type I, carboxy-terminal telopeptide of procollagen type I, and amino-terminal propeptide of procollagen type III are all elevated and serve as indicators of diastolic dysfunction. In these same patients, serum MMP-9 levels are elevated, suggesting increased degradation of myocardial collagen (Martos et al., 2007). This particular study elegantly demonstrated the role of MMP-9 in stimulating LV remodeling in hypertensive and diastolic heart failure patients.

3.5. MMP-9 roles in inflammation: neutrophils, macrophages, and lymphocytes are cell sources of MMP-9

MMP-9 is secreted by neutrophils early post-MI, and by macrophages, lymphocytes, and fibroblasts at later phases post-MI (Fig. 3). In neutrophils, MMP-9 is synthesized during bone marrow granulocyte differentiation and is released following neutrophil activation (Jonsson et al., 2011). Fang et al. quantified MMP-9 levels in peripheral blood mononuclear cells that were differentiated into macrophages in vitro (Fang et al., 2007). Circulating cells isolated at day 4 after MI in 129sv mice showed increased MMP-9 levels compared to cells isolated from the sham mice. Peripheral blood mononuclear cells isolated from patients with acute MI and differentiated to macrophages also produced a higher amount of MMP-9 compared to cells isolated from patients with stable angina or healthy controls, indicating that macrophages are an important cellular source of plasma MMP-9 (Fang et al., 2010).

3.6. MMP-9 effects on inflammatory chemokines and cytokines

MMP-9 modulates leukocyte function through a number of cytokine-mediated mechanisms. MMP-9 can process pro-IL-1β into active IL-1β and can truncate IL-8 into a more active form. As both IL-1β and IL-8 can stimulate MMP-9 degranulation from neutrophils, providing an important positive feedback loop for neutrophil activation and chemotaxis (Opdenakker et al., 2001).

In the post-MI setting, the overexpression of human CRP in mice results in more severe LV remodeling with increased LV dilation, a greater extent of LV dysfunction, and more prominent cardiomyocyte hypertrophy and fibrosis than their littermate controls (Mano et al., 2011). The CRP transgenic mice also display enhanced macrophage infiltration into the infarct region, at rates that are directly proportional to increased MCP-1 expression and MMP-9 activity (Takahashi et al., 2010). Increased CRP, therefore, leads to increased macrophage accumulation through a direct MMP-9 role.

3.7. MMP-9 inhibitors

It is well established that an increased expression of MMP-9 associates with the pathological status in a wide range of inflammatory diseases, including MI, rheumatoid arthritis, liver fibrosis, and periodontal disease. A pathogenic role of MMP-9 in tissue breakdown and remodeling during aggressive tumor growth and angiogenesis is also established. Because of past failures with global non-specific MMP inhibitors, the current focus in the MMP inhibitor drug discovery arena is to develop inhibitors specific for particular MMPs.

The main structural requirement of an MMP inhibitor is the zinc binding group (ZBG) that chelates the active-site zinc ion. Tandon and Sinha applied a docking and molecular dynamics approach to study the binding of inhibitors to the active site of MMP-9. Three categories of zinc binding groups were chosen: 1) sulfonamide hydroxamate, 2) thioester, and 3) carboxylic moieties. Out of these three categories, the thioester based zinc binding moiety provided the most promising docking scores compared to the other two groups (Tandon & Sinha, 2011).

Gutierrez and colleagues demonstrated that the MMP-9 inhibitor doxycline attenuated *Trypanosoma cruzi* infection induced cardiac injury (Gutierrez et al., 2008). These results indicate that MMP-9 inhibition in myocarditis mollifies inflammation to increase survival in mice (Gutierrez et al., 2008). Of interest, doxycycline is the only FDA-approved MMP inhibitor currently on the market (Lee et al., 2004; Zhang et al., 2012).

Pharmacological inhibition of MMPs has been effective in limiting tissue damage after MI in animal models. Villarreal et al. observed that short-term treatment of doxycline reduced adverse LV remodeling and improved LV function in male Sprague–Dawley rats (Villarreal et al., 2003). MMP inhibition in humans, however, has not been as successful, as broad-spectrum MMP inhibitors showed adverse secondary effects on the musculoskeletal system that were linked to the non-selective nature of these inhibitors (Creemers et al., 2001; Spinale, 2002).

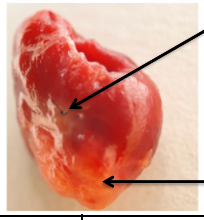
4. MMP-9 distal effects on other inflammatory diseases (Fig. 2)

4.1. Atherosclerosis

Atherosclerosis is an inflammatory disease characterized by plaque formation and artery wall thickening as a result of the accumulation of lipids. Atherosclerosis mainly affects vein grafts, arterial blood vessels, and also includes the accumulation of macrophages, low-density lipoproteins, plasma proteins that transport cholesterol, and triglycerides (Ross, 1999).

Konstantino et al. have reviewed the role of MMP-9 in the pathophysiology of atherosclerosis and plaque rupture (Konstantino et al., 2009). While other MMPs (including MMP-1, -2, -3, -7, -8, -10, -11, -12, and -13) have been evaluated, MMP-9 has been the most studied MMP in atherosclerosis pathology (Konstantino et al., 2009). Despite the number of studies that demonstrate increased MMP-9 levels in the atherosclerotic lesion, few studies have been designed to

A) infarcted left ventricle



B) time course

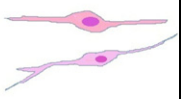
	Early phase	Intermediate phase	Late phase
Time (days)	1-2	3-7	>7
Cells involved	Myocytes Neutrophils	Neutrophils Macrophages Fibroblasts Endothelial cells Smooth muscle cells	Macrophages Fibroblasts Endothelial cells Smooth muscle cells
Major cell contributor of MMP-9	 Neutrophil	 Macrophage	 Fibroblast

Fig. 3. Schematic diagram presenting infarcted left ventricle and cell sources during the different stages of MMP-9 release as result of post-MI cardiac remodeling. **A**. Infarcted LV at 7 days post-MI. **B**. Following MI, MMP-9 is released by neutrophils in the early inflammatory phase (days 0–3), macrophages during the late inflammatory phase (days 3–7), and fibroblasts during the remodeling phase. Within the myocardium, cardiac myocytes, endothelial cells, and vascular smooth muscle cells are additional MMP-9 sources.

determine the causal roles of MMP-9 or to explore the clinical applicability of MMP-9 inhibition. Mechanistic studies in apolipoprotein E (Apo E)-null mice model provide conflicting insight on MMP-9 roles in plaque formation. Lutton et al. showed that after 25 weeks of a cholesterol-rich diet, Apo E/MMP-9 double-null mice had 70% smaller sized plaques with less collagen and macrophage content compared with Apo E null/MMP-$9^{+/+}$ mice, suggesting that MMP-9 deficiency protects from plaque development (Luttun et al., 2004).

Conversely, Johnson et al. demonstrated a larger lesion area and increased macrophage content in Apo E/ MMP-9 double-null mice compared with Apo E null/MMP-$9^{+/+}$ mice after 8 weeks of a high-fat diet, indicating that MMP-9 deficiency promoted rather than impaired atherosclerosis progression (Johnson et al., 2005). The inconsistent results could be ascribed to a variation in timing of lesion measurements, as Johnson et al. determined the lesion size after 8 weeks of a high-fat diet, whereas Lutton et al. assessed the lesion size after 25 weeks of a cholesterol-rich diet. The concept that MMP function can switch from deleterious to beneficial can be explained by a shift in substrate availability, since net MMP activity is determined by what substrates are processed. To support this idea, Nooijer et al. demonstrated that negative effects of MMP-9 overexpression on plaque stability appear to be more prominent in advanced atherosclerotic plaques (de Nooijer et al., 2006). Advanced plaques showed more significant features of vulnerable plaque with a high incidence of intra-plaque hemorrhage (de Nooijer et al., 2006). The overexpression of activated MMP-9 in macrophages induced substantial plaque disruption in advanced atherosclerotic lesions of Apo E null mice, revealing that enhanced macrophage MMP-9 proteolytic activity can induce acute plaque disruption. MMP-9, therefore, is a therapeutic target for stabilizing rupture-prone plaques that are in the advanced stage. The fact that MMP-9 and macrophages co-exist in vulnerable plaques highlights the role for MMP-9 in this process. Future studies examining the temporo-spatial dynamics of MMP-9 expression during plaque development and destabilization are required to fully understand the significance of MMP-9 activity in atherosclerosis (Gough et al., 2006). The cholesterol lowering drug statins (e.g. simvastatin, atorvastatin, and pravastatin) downregulate 3-hydroxy-3-methylglutaryl coenzyme A to improve plaque quality in atherosclerotic patients. Statins reduce macrophage accumulation and collagen degradation by reducing CD40 ligand/CD40 and expression of the adhesion molecule VCAM-1 (Libby & Aikawa, 2003).

4.2. Rheumatoid arthritis

Rheumatoid arthritis is a systemic inflammatory disorder that affects synovial joints. Patients with rheumatoid arthritis are more prone to atherosclerosis and have increased risks for MI and stroke (Symmons & Gabriel, 2011). The synovial fluid from patients of rheumatoid arthritis contains increased levels of MMP-9 (Ahrens et al., 1996; Yoshihara et al., 2000). Proteolytic degradation of articular cartilage is one of the early features of the disease and is mediated by an increased activity of MMP-3, -8, and -9 (Tchetverikov et al., 2003). In particular, MMP-9 cleavage of aggrecan releases multiple neo-epitopes that stimulate an immune response to both initiate the pathogenesis and aggravate the progression (Ram et al., 2006). MMP-9 increases in various autoimmune diseases such as systemic lupus erythematosus, Sjogren's syndrome, systemic sclerosis, multiple sclerosis, and polymyositis (Ram et al., 2006). Therefore, MMP-9 is considered an important target for therapy in autoimmune diseases.

4.3. Cancer

Cancer is a disease of dysregulated tissue growth. As cancer progresses, the uncontrolled growth often metastasizes and becomes invasive, wherein the tumor cells spread to other locations in the body via the lymphatic system or the bloodstream. MMPs are involved in many cancer-related processes including invasion, metastasis, angiogenesis, and cell proliferation (Egeblad & Werb, 2002). Although a number of MMPs (MMP-2, -7, -9, -11, and -14) are readily detected in most tumor types at all stages, the pattern of expression of other MMPs (MMP-1, -3 -8, -13) varies considerably by tumor type and stage.

Roy et al. reviewed the role of specific MMPs as novel biomarkers in different types of cancers such as breast (MMP-1, -9, -13), pancreas (MMP-2, -7, -9), lung (MMP-1, -7, -9), bladder (MMP-2, -9), colorectal (MMP-1, -2, -7, -9, -13), ovarian (2, -9, -14), prostate (MMP-2, -9) and brain (MMP-2, -9) (Roy et al., 2009). MMP-9 is in common to each of the above-mentioned cancers and has been proposed as an overarching biomarker of cancer. Further, MMP-9 has been shown to have epigenetic regulation that may provide additional biomarker candidates.

Cancer and cardiovascular disease intersect, as treatment strategies to fight cancer often induce cardiac dysfunction. One example of this is the use of anthracyclines (e.g., doxorubicin) as an anti-oncogenic therapy. Anthracyclines have known cardiotoxic side effects, including a significant activation of MMP-9 (Goetzenich et al., 2009). The inflammatory component is also a strong connection between these two diseases.

4.4. Periodontal disease

Periodontal disease is broadly classified into two subgroups: periodontitis and gingivitis. Periodontitis is an inflammatory disease that mainly affects the supporting tissues of the teeth leading to the progressive destruction of connective tissue attachments to alveolar bone. Gingivitis is a non-destructive inflammatory disease characterized by an increased build-up of plaque on tooth surfaces. Longtime untreated gingivitis progressing to periodontitis is the most destructive form of periodontal disease. MMP-8 and MMP-9 are major diagnostic markers that have been well described in periodontal disease (Ramseier et al., 2009). Periodontal disease shows a multifaceted pattern and progresses as a feed forward continuum of infection and inflammatory dysregulation with subsequent bone loss. Specific biomarkers, including MMP-8, MMP-9, IL-1β IL-6, and type I collagen pyridinoline cross-linked telopeptide (ICTP), have been used for periodontal disease identification (Ramseier et al., 2009).

4.5. Diabetes mellitus and vascular complications

Diabetes mellitus stimulates a strong the immune system response by upregulating specific cytokines, chemokines, and leukocyte populations to contribute to increased vascular cell apoptosis and tissue fibrosis during plaque formation (Donath & Shoelson, 2011). The increase in macrophage numbers associates with reduced collagen content and MMP-9 overexpression in human diabetic plaques (Cipollone et al., 2003). Furthermore, advanced glycation end products (the product of non-enzymatic glycation reactions stimulated by increased circulating glucose levels) stimulate COX-2/PGES-1 expression and induce MMP-9 synthesis in macrophages (Cipollone et al., 2003; Kadoglou & Liapis, 2004). Diabetes, therefore, exacerbates the inflammatory response in atherosclerosis.

Abdominal aortic aneurysms (AAAs) are a chronic degenerative condition associated with a risk of vessel wall rupture. AAAs develop due to the progressive degradation of aortic wall elastin and collagen, and an increase in the local production of MMP-9 has been implicated in this process. The FDA approved MMP-9 inhibitor doxycycline reduces MMP-9 expression in human vascular wall cell types and in AAA tissue explants in vitro. Patients administered with doxycycline also show suppressed MMP-9 expression in the AAA tissue (Kadoglou & Liapis, 2004; Thompson & Baxter, 1999).

5. Future directions

Based on the many proximal effects of MMP-9 on cardiac remodeling and the many distal effects of MMP-9 on inflammatory diseases demonstrated in both pre-clinical and clinical studies, the further exploration of MMP-9 inhibitors is justified for the development of novel cardiovascular agents that may benefit additional inflammatory diseases. Most currently used medications for heart failure (e.g., aldosterone antagonists, diuretics, ACE inhibitors, and beta-blockers) all decrease MMP-9 levels, indicating that screening for MMP-9 targets at early stages may help in the decision making process for cardiovascular drug discovery. While non-specific MMP inhibitor strategies have not proven useful (Peterson, 2004), a specific inhibitor strategy that targets MMP-9 may prove effective. Several groups, however, are making headway in the MMP specific inhibitor arena (Johnson et al., 2011; Robichaud et al., 2011).

There are several investigation streams that remain to be explored, before the potential of MMP-9 to serve as a diagnostic marker can be fully realized. These include:

a. MMP-9 specificity and selectivity as a biomarker and comparative advantages over current gold standard biomarkers such as BNP, N-terminal pro-BNP, troponin, or CRP need to be determined.
b. The associations between MMP-9 levels and common risk factors for cardiovascular disease, including obesity, hypertension, smoking, diabetes, and dyslipidemia need to be dissected.
c. Spatial and temporal MMP-9 patterns during the cardiac remodeling continuum and during other inflammatory disease (e.g. cancer, arthritis, and periodontal disease) are needed.
d. The spatial and temporal patterns of MMP-9, compared with the patterns of other MMPs in cardiac remodeling and inflammatory diseases, need to be determined.
e. Standardized procedures and practices are needed for the pre-analytical, analytical, and post-analytical platforms to evaluate MMP-9 performance.

6. Conclusions

Current pre-clinical and clinical documentation strongly support MMP-9 as a panel member in the biomarker list to diagnose or treat the pathophysiology of post-MI ventricular remodeling and congestive heart failure. Immune cells such as neutrophils or macrophages modify many processes in the MI response, and future research focused on biochemical and structural approaches to examine the ECM will likely provide new information on the remodeling process. Based on the evidence provided, further prospective studies are required to assess the prognostic value of MMP-9 for post-MI remodeling, particularly in comparison with traditional markers.

Conflict of interest statement

ML Lindsey and GV Halade have current grant funding from Amylin Pharmaceuticals. This article is unrelated to that project.

Acknowledgments

We acknowledge support from NIH-NCCAM K99AT006704 to GVH; from NSF 0649172, NIH EB009496, and NIH 1SC2 HL101430 to Y-FJ and from NHLBI HHSN 268201000036C (N01-HV-00244) for the UTHSCSA Cardiovascular Proteomics Center and R01 HL-075360, the Max and Minnie Tomerlin Voelcker Fund, and the Veteran's Administration (Merit) to MLL.

References

Ahrens, D., Koch, A. E., Pope, R. M., Stein-Picarella, M., & Niedbala, M. J. (1996). Expression of matrix metalloproteinase 9 (96-kd gelatinase B) in human rheumatoid arthritis. *Arthritis Rheum 39*, 1576–1587.

Balagopal, P. B., de Ferranti, S. D., Cook, S., Daniels, S. R., Gidding, S. S., Hayman, L. L., et al. (2011). Nontraditional risk factors and biomarkers for cardiovascular disease: mechanistic, research, and clinical considerations for youth: a scientific statement from the American Heart Association. *Circulation 123*, 2749–2769.

Bannikov, G. A., Karelina, T. V., Collier, I. E., Marmer, B. L., & Goldberg, G. I. (2002). Substrate binding of gelatinase B induces its enzymatic activity in the presence of intact propeptide. *J Biol Chem*, M110931200.

Benbow, U., & Brinckerhoff, C. E. (1997). The AP-1 site and MMP gene regulation: what is all the fuss about? *Matrix Biol 15*, 519–526.
Biomarkers Definitions Working Group (2001). Biomarkers and surrogate endpoints: preferred definitions and conceptual framework. *Clin Pharmacol Ther 69*, 89–95.
Blankenberg, S., Rupprecht, H. J., Poirier, O., Bickel, C., Smieja, M., Hafner, G., et al. (2003). Plasma concentrations and genetic variation of matrix metalloproteinase 9 and prognosis of patients with cardiovascular disease. *Circulation 107*, 1579–1585.
Braunwald, E. (2008). Biomarkers in heart failure. *N Engl J Med 358*, 2148–2159.
Chancey, A. L., Brower, G. L., Peterson, J. T., & Janicki, J. S. (2002). Effects of matrix metalloproteinase inhibition on ventricular remodeling due to volume overload. *Circulation 105*, 1983–1988.
Chiao, Y. A., Dai, Q., Zhang, J., Lin, J., Lopez, E. F., Ahuja, S. S., et al. (2011). Multi-analyte profiling reveals matrix metalloproteinase-9 and monocyte chemotactic protein-1 as plasma biomarkers of cardiac aging. *Circ Cardiovasc Genet 4*, 455–462.
Cipollone, F., Iezzi, A., Fazia, M., Zucchelli, M., Pini, B., Cuccurullo, C., et al. (2003). The receptor RAGE as a progression factor amplifying arachidonate-dependent inflammatory and proteolytic response in human atherosclerotic plaques: role of glycemic control. *Circulation 108*, 1070–1077.
Coker, M. L., Jolly, J. R., Joffs, C., Etoh, T., Holder, J. R., Bond, B. R., et al. (2001). Matrix metalloproteinase expression and activity in isolated myocytes after neurohormonal stimulation. *Am J Physiol Heart Circ Physiol 281*, H543–H551.
Creemers, E. E., Cleutjens, J. P., Smits, J. F., & Daemen, M. J. (2001). Matrix metalloproteinase inhibition after myocardial infarction: a new approach to prevent heart failure? *Circ Res 89*, 201–210.
de Nooijer, R., Verkleij, C. J., von der Thusen, J. H., Jukema, J. W., van der Wall, E. E., van Berkel, T. J., et al. (2006). Lesional overexpression of matrix metalloproteinase-9 promotes intraplaque hemorrhage in advanced lesions but not at earlier stages of atherogenesis. *Arterioscler Thromb Vasc Biol 26*, 340–346.
Dobaczewski, M., Gonzalez-Quesada, C., & Frangogiannis, N. G. (2010). The extracellular matrix as a modulator of the inflammatory and reparative response following myocardial infarction. *J Mol Cell Cardiol 48*, 504–511.
Donath, M. Y., & Shoelson, S. E. (2011). Type 2 diabetes as an inflammatory disease. *Nat Rev Immunol 11*, 98–107.
Ducharme, A., Frantz, S., Aikawa, M., Rabkin, E., Lindsey, M., Rohde, L. E., et al. (2000). Targeted deletion of matrix metalloproteinase-9 attenuates left ventricular enlargement and collagen accumulation after experimental myocardial infarction. *J Clin Invest 106*, 55–62.
Egeblad, M., & Werb, Z. (2002). New functions for the matrix metalloproteinases in cancer progression. *Nat Rev Cancer 2*, 161–174.
Etoh, T., Joffs, C., Deschamps, A. M., Davis, J., Dowdy, K., Hendrick, J., et al. (2001). Myocardial and interstitial matrix metalloproteinase activity after acute myocardial infarction in pigs. *Am J Physiol Heart Circ Physiol 281*, H987–H994.
Fang, L., Du, X. J., Gao, X. M., & Dart, A. M. (2010). Activation of peripheral blood mononuclear cells and extracellular matrix and inflammatory gene profile in acute myocardial infarction. *Clin Sci 119*, 175–183.
Fang, L., Gao, X. M., Moore, X. L., Kiriazis, H., Su, Y., Ming, Z., et al. (2007). Differences in inflammation, MMP activation and collagen damage account for gender difference in murine cardiac rupture following myocardial infarction. *J Mol Cell Cardiol 43*, 535–544.
Fertin, M., Dubois, E., Belliard, A., Amouyel, P., Pinet, F., & Bauters, C. (2012). Usefulness of circulating biomarkers for the prediction of left ventricular remodeling after myocardial infarction. *Am J Cardiol 110*, 277–283.
Figueras, J., Cortadellas, J., & Soler-Soler, J. (2000). Left ventricular free wall rupture: clinical presentation and management. *Heart 83*, 499–504.
Fortmann, S. P., Ford, E., Criqui, M. H., Folsom, A. R., Harris, T. B., Hong, Y., et al. (2004). CDC/AHA Workshop on Markers of Inflammation and Cardiovascular Disease: Application to Clinical and Public Health Practice: report from the population science discussion group. *Circulation 110*, e554–e559.
Frantz, S., Bauersachs, J., & Ertl, G. (2009). Post-infarct remodelling: contribution of wound healing and inflammation. *Cardiovasc Res 81*, 474–481.
Gao, X. M., Xu, Q., Kiriazis, H., Dart, A. M., & Du, X. J. (2005). Mouse model of post-infarct ventricular rupture: time course, strain- and gender-dependency, tensile strength, and histopathology. *Cardiovasc Res 65*, 469–477.
Gerszten, R. E., Asnani, A., & Carr, S. A. (2011). Status and prospects for discovery and verification of new biomarkers of cardiovascular disease by proteomics. *Circ Res 109*, 463–474.
Goetzenich, A., Hatam, N., Zernecke, A., Weber, C., Czarnotta, T., Autschbach, R., et al. (2009). Alteration of matrix metalloproteinases in selective left ventricular adriamycin-induced cardiomyopathy in the pig. *J Heart Lung Transplant 28*, 1087–1093.
Goldberg, R. J., Ciampa, J., Lessard, D., Meyer, T. E., & Spencer, F. A. (2007). Long-term survival after heart failure: a contemporary population-based perspective. *Arch Intern Med 167*, 490–496.
Gough, P. J., Gomez, I. G., Wille, P. T., & Raines, E. W. (2006). Macrophage expression of active MMP-9 induces acute plaque disruption in apoE-deficient mice. *J Clin Invest 116*, 59–69.
Gu, Z., Kaul, M., Yan, B., Kridel, S. J., Cui, J., Strongin, A., et al. (2002). S-nitrosylation of matrix metalloproteinases: signaling pathway to neuronal cell death. *Science 297*, 1186–1190.
Gutierrez, F. R., Lalu, M. M., Mariano, F. S., Milanezi, C. M., Cena, J., Gerlach, R. F., et al. (2008). Increased activities of cardiac matrix metalloproteinases matrix metalloproteinase (MMP)-2 and MMP-9 are associated with mortality during the acute phase of experimental *Trypanosoma cruzi* infection. *J Infect Dis 197*, 1468–1476.
Hansson, J., Vasan, R. S., Arnlov, J., Ingelsson, E., Lind, L., Larsson, A., et al. (2011). Biomarkers of extracellular matrix metabolism (MMP-9 and TIMP-1) and risk of stroke, myocardial infarction, and cause-specific mortality: cohort study. *PLoS One 6*, e16185.
Hasty, K. A., Pourmotabbed, T. F., Goldberg, G. I., Thompson, J. P., Spinella, D. G., Stevens, R. M., et al. (1990). Human neutrophil collagenase. A distinct gene product with homology to other matrix metalloproteinases. *J Biol Chem 265*, 11421–11424.
Heymans, S., Luttun, A., Nuyens, D., Theilmeier, G., Creemers, E., Moons, L., et al. (1999). Inhibition of plasminogen activators or matrix metalloproteinases prevents cardiac rupture but impairs therapeutic angiogenesis and causes cardiac failure. *Nat Med 5*, 1135–1142.
Hlatky, M. A., Ashley, E., Quertermous, T., Boothroyd, D. B., Ridker, P., Southwick, A., et al. (2007). Matrix metalloproteinase circulating levels, genetic polymorphisms, and susceptibility to acute myocardial infarction among patients with coronary artery disease. *Am Heart J 154*, 1043–1051.
Hlatky, M. A., Greenland, P., Arnett, D. K., Ballantyne, C. M., Criqui, M. H., Elkind, M. S., et al. (2009). Criteria for evaluation of novel markers of cardiovascular risk: a scientific statement from the American Heart Association. *Circulation 119*, 2408–2416.
Horwich, T. B., & Fonarow, G. C. (2010). Glucose, obesity, metabolic syndrome, and diabetes relevance to incidence of heart failure. *J Am Coll Cardiol 55*, 283–293.
Hudson, M. P., Armstrong, P. W., Ruzyllo, W., Brum, J., Cusmano, L., Krzeski, P., et al. (2006). Effects of selective matrix metalloproteinase inhibitor (PG-116800) to prevent ventricular remodeling after myocardial infarction: results of the PREMIER (Prevention of Myocardial Infarction Early Remodeling) trial. *J Am Coll Cardiol 48*, 15–20.
Johnson, J. L., Devel, L., Czarny, B., George, S. J., Jackson, C. L., Rogakos, V., et al. (2011). A selective matrix metalloproteinase-12 inhibitor retards atherosclerotic plaque development in apolipoprotein E-knockout mice. *Arterioscler Thromb Vasc Biol 31*, 528–535.
Johnson, J. L., George, S. J., Newby, A. C., & Jackson, C. L. (2005). Divergent effects of matrix metalloproteinases 3, 7, 9, and 12 on atherosclerotic plaque stability in mouse brachiocephalic arteries. *Proc Natl Acad Sci U S A 102*, 15575–15580.
Jonsson, S., Lundberg, A., Kalvegren, H., Bergstrom, I., Szymanowski, A., & Jonasson, L. (2011). Increased levels of leukocyte-derived MMP-9 in patients with stable angina pectoris. *PLoS One 6*, e19340.
Kadoglou, N. P., & Liapis, C. D. (2004). Matrix metalloproteinases: contribution to pathogenesis, diagnosis, surveillance and treatment of abdominal aortic aneurysms. *Curr Med Res Opin 20*, 419–432.
Kawakami, R., Saito, Y., Kishimoto, I., Harada, M., Kuwahara, K., Takahashi, N., et al. (2004). Overexpression of brain natriuretic peptide facilitates neutrophil infiltration and cardiac matrix metalloproteinase-9 expression after acute myocardial infarction. *Circulation 110*, 3306–3312.
Kelly, D., Cockerill, G., Ng, L. L., Thompson, M., Khan, S., Samani, N. J., et al. (2007). Plasma matrix metalloproteinase-9 and left ventricular remodelling after acute myocardial infarction in man: a prospective cohort study. *Eur Heart J 28*, 711–718.
Kobayashi, N., Hata, N., Kume, N., Yokoyama, S., Shinada, T., Tomita, K., et al. (2011). Matrix metalloproteinase-9 for the earliest stage acute coronary syndrome. *Circ J 75*(12), 2853–28561 (Epub 2011 Oct 1).
Konstantino, Y., Nguyen, T. T., Wolk, R., Aiello, R. J., Terra, S. G., & Fryburg, D. A. (2009). Potential implications of matrix metalloproteinase-9 in assessment and treatment of coronary artery disease. *Biomarkers 14*, 118–129.
Krishna, R., Herman, G., & Wagner, J. A. (2008). Accelerating drug development using biomarkers: a case study with sitagliptin, a novel DPP4 inhibitor for type 2 diabetes. *AAPS J 10*, 401–409.
Krishna, R., & Wagner, J. A. (2010). Applications of 'decisionable' biomarkers in cardiovascular drug development. *Biomark Med 4*, 815–827.
Lang, C. C., & Mancini, D. M. (2007). Non-cardiac comorbidities in chronic heart failure. *Heart 93*, 665–671.
Lauer-Fields, J. L., Whitehead, J. K., Li, S., Hammer, R. P., Brew, K., & Fields, G. B. (2008). Selective modulation of matrix metalloproteinase 9 (MMP-9) functions via exosite inhibition. *J Biol Chem 283*, 20087–20095.
Lee, H. M., Ciancio, S. G., Tuter, G., Ryan, M. E., Komaroff, E., & Golub, L. M. (2004). Subantimicrobial dose doxycycline efficacy as a matrix metalloproteinase inhibitor in chronic periodontitis patients is enhanced when combined with a non-steroidal anti-inflammatory drug. *J Periodontol 75*, 453–463.
Libby, P., & Aikawa, M. (2003). Mechanisms of plaque stabilization with statins. *Am J Cardiol 91*, 4B–8B.
Lindsey, M. L. (2004). MMP induction and inhibition in myocardial infarction. *Heart Fail Rev 9*, 7–19.
Lindsey, M. L., Escobar, G. P., Dobrucki, L. W., Goshorn, D. K., Bouges, S., Mingoia, J. T., et al. (2006a). Matrix metalloproteinase-9 gene deletion facilitates angiogenesis after myocardial infarction. *Am J Physiol Heart Circ Physiol 290*, H232–H239.
Lindsey, M. L., Escobar, G. P., Mukherjee, R., Goshorn, D. K., Sheats, N. J., Bruce, J. A., et al. (2006b). Matrix metalloproteinase-7 affects connexin-43 levels, electrical conduction, and survival after myocardial infarction. *Circulation 113*, 2919–2928.
Lindsey, M. L., Goshorn, D. K., Squires, C. E., Escobar, G. P., Hendrick, J. W., Mingoia, J. T., et al. (2005). Age-dependent changes in myocardial matrix metalloproteinase/tissue inhibitor of metalloproteinase profiles and fibroblast function. *Cardiovasc Res 66*, 410–419.
Lindsey, M., Wedin, K., Brown, M. D., Keller, C., Evans, A. J., Smolen, J., et al. (2001). Matrix-dependent mechanism of neutrophil-mediated release and activation of matrix metalloproteinase 9 in myocardial ischemia/reperfusion. *Circulation 103*, 2181–2187.
Lindsey, M. L., & Zamilpa, R. (2012). Temporal and spatial expression of matrix metalloproteinases and tissue inhibitors of metalloproteinases following myocardial infarction. *Cardiovasc Ther 30*(1), 31–41.
Lopez-Sendon, J., Gurfinkel, E. P., Lopez de Sa, E., Agnelli, G., Gore, J. M., Steg, P. G., et al. (2010). Factors related to heart rupture in acute coronary syndromes in the Global Registry of Acute Coronary Events. *Eur Heart J 31*, 1449–1456.
Luttun, A., Lutgens, E., Manderveld, A., Maris, K., Collen, D., Carmeliet, P., et al. (2004). Loss of matrix metalloproteinase-9 or matrix metalloproteinase-12 protects apolipoprotein E-deficient mice against atherosclerotic media destruction but differentially affects plaque growth. *Circulation 109*, 1408–1414.

Maisel, A. S., Krishnaswamy, P., Nowak, R. M., McCord, J., Hollander, J. E., Duc, P., et al. (2002). Rapid measurement of B-type natriuretic peptide in the emergency diagnosis of heart failure. *N Engl J Med 347*, 161–167.

Mano, Y., Anzai, T., Kaneko, H., Nagatomo, Y., Nagai, T., Anzai, A., et al. (2011). Overexpression of human C-reactive protein exacerbates left ventricular remodeling in diabetic cardiomyopathy. *Circ J 75*, 1717–1727.

Martos, R., Baugh, J., Ledwidge, M., O'Loughlin, C., Conlon, C., Patle, A., et al. (2007). Diastolic heart failure: evidence of increased myocardial collagen turnover linked to diastolic dysfunction. *Circulation 115*, 888–895.

Mukherjee, R., Brinsa, T. A., Dowdy, K. B., Scott, A. A., Baskin, J. M., Deschamps, A. M., et al. (2003). Myocardial infarct expansion and matrix metalloproteinase inhibition. *Circulation 107*, 618–625.

Mukherjee, R., Colbath, G. P., Justus, C. D., Bruce, J. A., Allen, C. M., Hewett, K. W., et al. (2010). Spatiotemporal induction of matrix metalloproteinase-9 transcription after discrete myocardial injury. *FASEB J 24*, 3819–3828.

Mukherjee, R., Mingoia, J. T., Bruce, J. A., Austin, J. S., Stroud, R. E., Escobar, G. P., et al. (2006). Selective spatiotemporal induction of matrix metalloproteinase-2 and matrix metalloproteinase-9 transcription after myocardial infarction. *Am J Physiol Heart Circ Physiol 291*(5), H2216–H2228.

Nagase, H., Visse, R., & Murphy, G. (2006). Structure and function of matrix metalloproteinases and TIMPs. *Cardiovasc Res 69*, 562–573.

Opdenakker, G., Van den Steen, P. E., Dubois, B., Nelissen, I., Van Coillie, E., Masure, S., et al. (2001). Gelatinase B functions as regulator and effector in leukocyte biology. *J Leukoc Biol 69*, 851–859.

Orn, S., Manhenke, C., Squire, I. B., Ng, L., Anand, I., & Dickstein, K. (2007). Plasma MMP-2, MMP-9 and N-BNP in long-term survivors following complicated myocardial infarction: relation to cardiac magnetic resonance imaging measures of left ventricular structure and function. *J Card Fail 13*(10), 843–849.

Peppin, G. J., & Weiss, S. J. (1986). Activation of the endogenous metalloproteinase, gelatinase, by triggered human neutrophils. *Proc Natl Acad Sci U S A 83*, 4322–4326.

Peterson, J. T. (2004). Matrix metalloproteinase inhibitor development and the remodeling of drug discovery. *Heart Fail Rev 9*, 63–79.

Pfeffer, M. A., & Braunwald, E. (1990). Ventricular remodeling after myocardial infarction. Experimental observations and clinical implications. *Circulation 81*, 1161–1172.

Porter, K. E., & Turner, N. A. (2009). Cardiac fibroblasts: at the heart of myocardial remodeling. *Pharmacol Ther 123*, 255–278.

Ram, M., Sherer, Y., & Shoenfeld, Y. (2006). Matrix metalloproteinase-9 and autoimmune diseases. *J Clin Immunol 26*, 299–307.

Ramani, R., Mathier, M., Wang, P., Gibson, G., Togel, S., Dawson, J., et al. (2004). Inhibition of tumor necrosis factor receptor-1-mediated pathways has beneficial effects in a murine model of postischemic remodeling. *Am J Physiol Heart Circ Physiol 287*, H1369–H1377.

Ramseier, C. A., Kinney, J. S., Herr, A. E., Braun, T., Sugai, J. V., Shelburne, C. A., et al. (2009). Identification of pathogen and host-response markers correlated with periodontal disease. *J Periodontol 80*, 436–446.

Reardon, M. J., Carr, C. L., Diamond, A., Letsou, G. V., Safi, H. J., Espada, R., et al. (1997). Ischemic left ventricular free wall rupture: prediction, diagnosis, and treatment. *Ann Thorac Surg 64*, 1509–1513.

Richards, A. M. (2009). What we may expect from biomarkers in heart failure. *Heart Fail Clin 5*, 463–470.

Robichaud, T. K., Steffensen, B., & Fields, G. B. (2011). Exosite interactions impact matrix metalloproteinase collagen specificities. *J Biol Chem 286*, 37535–37542.

Roger, V. L., Go, A. S., Lloyd-Jones, D. M., Adams, R. J., Berry, J. D., Brown, T. M., et al. (2011). Heart disease and stroke statistics — 2011 update: a report from the American Heart Association. *Circulation 123*, e18–e209.

Rohde, L. E., Ducharme, A., Arroyo, L. H., Aikawa, M., Sukhova, G. H., Lopez-Anaya, A., et al. (1999). Matrix metalloproteinase inhibition attenuates early left ventricular enlargement after experimental myocardial infarction in mice. *Circulation 99*, 3063–3070.

Romanic, A. M., Burns-Kurtis, C. L., Gout, B., Berrebi-Bertrand, I., & Ohlstein, E. H. (2001). Matrix metalloproteinase expression in cardiac myocytes following myocardial infarction in the rabbit. *Life Sci 68*, 799–814.

Ross, R. (1999). Atherosclerosis is an inflammatory disease. *Am Heart J 138*, S419–S420.

Roy, R., Yang, J., & Moses, M. A. (2009). Matrix metalloproteinases as novel biomarkers and potential therapeutic targets in human cancer. *Clin Oncol 27*(31), 5287–5297.

Shipley, J. M., Doyle, G. A., Fliszar, C. J., Ye, Q. Z., Johnson, L. L., Shapiro, S. D., et al. (1996). The structural basis for the elastolytic activity of the 92-kDa and 72-kDa gelatinases. Role of the fibronectin type II-like repeats. *J Biol Chem 271*, 4335–4341.

Sim, E. K., Zhang, L., Shim, W. S., Lim, Y. L., & Ge, R. (2002). Therapeutic angiogenesis for coronary artery disease. *J Card Surg 17*(4), 350–354.

Smith, S. C., Jr., Anderson, J. L., Cannon, R. O., III, Fadl, Y. Y., Koenig, W., Libby, P., et al. (2004). CDC/AHA Workshop on Markers of Inflammation and Cardiovascular Disease: Application to Clinical and Public Health Practice: report from the clinical practice discussion group. *Circulation 110*, e550–e553.

Sorokin, L. (2010). The impact of the extracellular matrix on inflammation. *Nat Rev Immunol 10*, 712–723.

Spinale, F. G. (2002). Matrix metalloproteinases: regulation and dysregulation in the failing heart. *Circ Res 90*, 520–530.

Spinale, F. G., Coker, M. L., Krombach, S. R., Mukherjee, R., Hallak, H., Houck, W. V., et al. (1999). Matrix metalloproteinase inhibition during the development of congestive heart failure: effects on left ventricular dimensions and function. *Circ Res 85*, 364–376.

Squire, I. B., Evans, J., Ng, L. L., Loftus, I. M., & Thompson, M. M. (2004). Plasma MMP-9 and MMP-2 following acute myocardial infarction in man: correlation with echocardiographic and neurohumoral parameters of left ventricular dysfunction. *J Card Fail 10*, 328–333.

Sternlicht, M. D., & Werb, Z. (2001). How matrix metalloproteinases regulate cell behavior. *Annu Rev Cell Dev Biol 17*, 463–516.

Sundstrom, J., Evans, J. C., Benjamin, E. J., Levy, D., Larson, M. G., Sawyer, D. B., et al. (2004). Relations of plasma matrix metalloproteinase-9 to clinical cardiovascular risk factors and echocardiographic left ventricular measures: the Framingham Heart Study. *Circulation 109*, 2850–2856.

Symmons, D. P., & Gabriel, S. E. (2011). Epidemiology of CVD in rheumatic disease, with a focus on RA and SLE. *Nat Rev Rheumatol 7*, 399–408.

Takahashi, T., Anzai, T., Kaneko, H., Mano, Y., Anzai, A., Nagai, T., et al. (2010). Increased C-reactive protein expression exacerbates left ventricular dysfunction and remodeling after myocardial infarction. *Am J Physiol Heart Circ Physiol 299*, H1795–H1804.

Tandon, A., & Sinha, S. (2011). Structural insights into the binding of MMP9 inhibitors. *Bioinformation 5*, 310–314.

Tang, W. H., Francis, G. S., Morrow, D. A., Newby, L. K., Cannon, C. P., Jesse, R. L., et al. (2007). National Academy of Clinical Biochemistry Laboratory Medicine practice guidelines: clinical utilization of cardiac biomarker testing in heart failure. *Circulation 116*, e99–e109.

Tanner, R. M., Lynch, A. I., Brophy, V. H., Eckfeldt, J. H., Davis, B. R., Ford, C. E., et al. (2011). Pharmacogenetic associations of MMP9 and MMP12 variants with cardiovascular disease in patients with hypertension. *PLoS One 6*, e23609.

Tao, Z. Y., Cavasin, M. A., Yang, F., Liu, Y. H., & Yang, X. P. (2004). Temporal changes in matrix metalloproteinase expression and inflammatory response associated with cardiac rupture after myocardial infarction in mice. *Life Sci 74*, 1561–1572.

Tchetverikov, I., Lard, L. R., DeGroot, J., Verzijl, N., TeKoppele, J. M., Breedveld, F. C., et al. (2003). Matrix metalloproteinases-3, -8, -9 as markers of disease activity and joint damage progression in early rheumatoid arthritis. *Ann Rheum Dis 62*, 1094–1099.

Thompson, R. W., & Baxter, B. T. (1999). MMP inhibition in abdominal aortic aneurysms. Rationale for a prospective randomized clinical trial. *Ann N Y Acad Sci 878*, 159–178.

van den Borne, S. W., Cleutjens, J. P., Hanemaaijer, R., Creemers, E. E., Smits, J. F., Daemen, M. J., et al. (2009). Increased matrix metalloproteinase-8 and -9 activity in patients with infarct rupture after myocardial infarction. *Cardiovasc Pathol 18*, 37–43.

Van Den Steen, P. E., Wuyts, A., Husson, S. J., Proost, P., Van Damme, J., & Opdenakker, G. (2003). Gelatinase B/MMP-9 and neutrophil collagenase/MMP-8 process the chemokines human GCP-2/CXCL6, ENA-78/CXCL5 and mouse GCP-2/LIX and modulate their physiological activities. *Eur J Biochem 270*, 3739–3749.

Vasan, R. S. (2006). Biomarkers of cardiovascular disease: molecular basis and practical considerations. *Circulation 113*, 2335–2362.

Velagaleti, R. S., Gona, P., Larson, M. G., Wang, T. J., Levy, D., Benjamin, E. J., et al. (2010). Multimarker approach for the prediction of heart failure incidence in the community. *Circulation 122*, 1700–1706.

Villarreal, F. J., Griffin, M., Omens, J., Dillmann, W., Nguyen, J., & Covell, J. (2003). Early short-term treatment with doxycycline modulates postinfarction left ventricular remodeling. *Circulation 108*, 1487–1492.

Yan, A. T., Yan, R. T., Spinale, F. G., Afzal, R., Gunasinghe, H. R., Arnold, M., et al. (2006). Plasma matrix metalloproteinase-9 level is correlated with left ventricular volumes and ejection fraction in patients with heart failure. *J Card Fail 12*, 514–519.

Yang, Y., Ma, Y., Han, W., Li, J., Xiang, Y., Liu, F., et al. (2008). Age-related differences in postinfarct left ventricular rupture and remodeling. *Am J Physiol Heart Circ Physiol 294*, H1815–H1822.

Yarbrough, W. M., Mukherjee, R., Escobar, G. P., Mingoia, J. T., Sample, J. A., Hendrick, J. W., et al. (2003). Selective targeting and timing of matrix metalloproteinase inhibition in post-myocardial infarction remodeling. *Circulation 108*, 1753–1759.

Yoshihara, Y., Nakamura, H., Obata, K., Yamada, H., Hayakawa, T., Fujikawa, K., et al. (2000). Matrix metalloproteinases and tissue inhibitors of metalloproteinases in synovial fluids from patients with rheumatoid arthritis or osteoarthritis. *Ann Rheum Dis 59*, 455–461.

Zamilpa, R., Kanakia, R., Cigarroa, J. t., Dai, Q., Escobar, G. P., Martinez, H. M., et al. (2011). CC chemokine receptor 5 deletion impairs macrophage activation and induces adverse remodeling following myocardial infarction. *Am J Physiol Heart Circ Physiol 300*(4), H1418–H1426.

Zamilpa, R., & Lindsey, M. L. (2010). Extracellular matrix turnover and signaling during cardiac remodeling following MI: causes and consequences. *J Mol Cell Cardiol 48*, 558–563.

Zamilpa, R., Lopez, E. F., Chiao, Y. A., Dai, Q., Escobar, G. P., Hakala, K., et al. (2010). Proteomic analysis identifies in vivo candidate matrix metalloproteinase-9 substrates in the left ventricle post-myocardial infarction. *Proteomics 10*, 2214–2223.

Zhang, Y., Gu, Y., Lee, H. M., Hambardjieva, E., Vrankova, K., Golub, L. M., et al. (2012). Design, synthesis and biological activity of new polyenolic inhibitors of matrix metalloproteinases: a focus on chemically-modified curcumins. *Curr Med Chem 19*, 4348–4358.

Zhang, B., Ye, S., Herrmann, S. M., Eriksson, P., de Maat, M., Evans, A., et al. (1999). Functional polymorphism in the regulatory region of gelatinase B gene in relation to severity of coronary atherosclerosis. *Circulation 99*, 1788–1794.