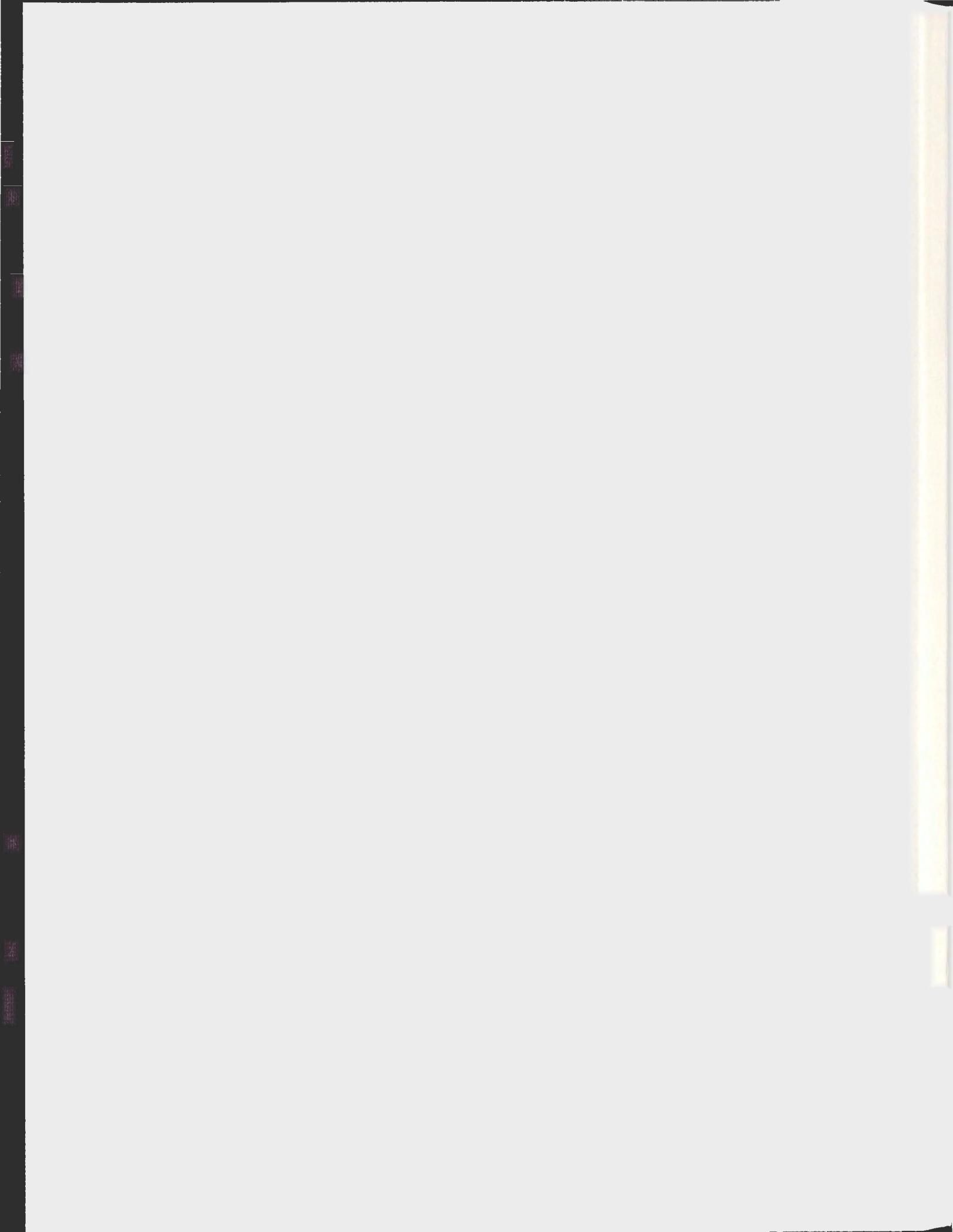


EFFECTS OF CHRONIC SUBCUTANEOUS ADMINISTERED  
PROTEINASE-ACTIVATED RECEPTOR 2-ACTIVATING  
PEPTIDE ON VASCULAR REACTIVITY OF AORTAS  
AND BLOOD PRESSURES IN MICE

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**Effects of chronic subcutaneous administered proteinase-activated receptor 2-activating peptide on vascular reactivity of aortas and blood pressures in mice.**

By

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## Abstract

The acute *in vivo* effects of proteinase-activated receptor 2 activating peptides (PAR<sub>2</sub>-AP) are reported to include vascular inflammation and hypotension. We studied the time- (7 and 14 days) and dose-dependent (2 nmol/kg/min and 6 nmol/kg/min) effects of chronic subcutaneous infusion with a PAR<sub>2</sub>-AP, 2-furoyl-LIGRLO-NH<sub>2</sub> (2fly), in C57BL/6J (C57) mice and PAR<sub>2</sub>-deficient (PAR<sub>2</sub><sup>-/-</sup>) mice. In aortas from PAR<sub>2</sub>-AP treated C57 mice the relaxation curve generated by 2fly was rightwardly shifted relative to saline-treated C57 mice. At specific times and doses of PAR<sub>2</sub>-AP treatment in C57 mice, the maximal endothelium-dependent (acetylcholine) and -independent (nitroprusside) nitric oxide-mediated relaxations of aortas were less than in saline-treated C57. Aortic expression of proteins associated with PAR<sub>2</sub>-AP induced smooth muscle relaxation was not significantly different between mouse strains and treatment groups. In C57 mice, 24 h hemodynamics and locomotor activity measured by radiotelemetry throughout the infusion periods indicated that 2fly high dose treatment lowered arterial systolic and pulse pressures relative to the baseline period when compared to saline infusions. We conclude that PAR<sub>2</sub>-AP administered chronically *in vivo* produced aortic dysfunction in C57 mice which was characterized by attenuated endothelium-dependent PAR<sub>2</sub>, cholinergic, and endothelium-independent nitric oxide-mediated relaxations. In spite of the *in vivo* vascular dysfunction, high dose 2fly-treatment lowered the systolic and pulse blood pressures of C57 mice.

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Secondly, I would like to thank the faculty and staff of the Cardiovascular and Renal Sciences Group of Memorial University. I would like to thank Dr. John Smeda and Dr. Bruno Stuyvers for their help during development of different stages of my experiments as well as providing great advice. I would also like to thank Dr. Bruce Van Vliet for guidance on telemetry. Many others have helped me in many ways throughout my thesis. Sarah Halfyard, Elizabeth Chia, Dr. Enoka Wijekoon, Dr. Satomi Kagota, and Dr. Noriko Daneshtalab have all helped me learn different techniques while providing a friendly and enjoyable environment in which to work. Finally, I am thankful for encouragement and support from Santana and my parents. Without their help completion of my thesis would have not been possible.

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## **Co-Authorship**

This thesis was based on research completed under the primary supervision of Dr. John McGuire and thesis supervisory committee members Dr. John Smeda and Dr. Bruno Stuyvers of the Cardiovascular-Renal Sciences Graduate Studies Program. Supervisors provided assistance with the research proposal, experimental design, and preparation of written work contained within.

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## List of Abbreviations

- 2fly – 2-furoyl-LIGRLO-NH<sub>2</sub>
- A23187 – calcium ionophore
- ACh – acetylcholine
- BP – blood pressure
- C57– C57BL/6J mice
- cGMP – 3, 5 cyclic guanosine monophosphate
- COX-*n* – cyclooxygenase-*n*, where *n* = 1 or 2
- CRC – concentration response curve
- DNA – deoxyribonucleic acid
- ENMD-1068 – *N*1-3-methylbutyryl-*N*4-6-aminohexanoyl-piperazine
- eNOS – endothelial nitric oxide synthase
- FITC – fluorescein isothiocyanate
- GTP – guanosine triphosphate
- i.v. – intravenous
- IL-*n* – interleukin, where *n*= the interleukin number
- L-NAME – *N*ω-nitro-L-arginine-methyl ester
- M3 – type 3 muscarinic receptor
- NO – nitric oxide
- PAR*n* – proteinase-activated receptor *n*, where *n*=1, 2, 3 or 4; also known as protease-activated receptors

*PAR<sub>2</sub>* – also known as factor 2 receptor like 1 (*F2rl1*); GPCR-11

*PAR<sub>2</sub><sup>-/-</sup>* – proteinase-activated receptor 2 knockout mice (B6.Cg-*F2rl1*<sup>tm1Mslb</sup>/J)

PAR-AP – PAR-activating peptide

s.c. – subcutaneous

sGC – soluble guanylyl cyclase

U46619 – 9, 11-dideoxy-11 $\alpha$ , 9 $\alpha$ -epoxymethanoprostaglandin F<sub>2 $\alpha$</sub>

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# Chapter 1: Introduction

## 1.1 Research problem

Cardiovascular diseases including myocardial infarction, stroke, and ischemic heart disease, accounted for 30% of all deaths in Canada during the years 2000 to 2006 (Statistics Canada, 2010). Hypertension is a major risk factor for these diseases and is one of the most common chronic clinical pathologies in Canadians. Hypertension has many underlying causes. A well known cause is increased peripheral vascular resistance to blood flow; this has been in part attributed to increased level of endothelium-derived contracting factors and decreased levels of endothelium-derived relaxing factors (Harrison, 1997). The constant imbalance of vasoactive substances in a blood vessel such that there is greater amounts of vasoconstrictive compared to vasorelaxant effects resulting in elevated blood pressure (BP) is one definition that is used to describe endothelial dysfunction. Increased blood pressure may lead to vascular damage (damage to the membrane integrity of the endothelium), which can be followed by inflammatory processes leading to atherosclerosis (Deanfield *et al.*, 2005). Endothelial dysfunction is associated with hypercholesterolemia, type 2 diabetes, and chronic inflammation (Brunner *et al.*, 2005). The interactions of endothelial dysfunction with multiple diseases makes this topic an area of research that needs to be further studied. It is possible that an intervention or functional offset of endothelial dysfunction may be a therapeutic benefit in cardiovascular diseases.

One possible target for intervention of endothelial dysfunction is PAR<sub>2</sub>. In many studies, when this receptor was activated acutely it decreased inflammation pathologies (Kelso *et al.*, 2006, Lindner *et al.*, 2000; Schmidlin *et al.*, 2002; Robin *et al.*, 2003; Seeliger *et al.*, 2003) and lowered blood pressure (Cheung *et al.*, 1998; Damiano *et al.*, 1999; Wang *et al.*, 2010). A study of chronic activation of PAR<sub>2</sub> would add to the knowledge on how the body may function under the influence of a receptor system with capability for modulating both inflammation and vasorelaxation.

## **1.2 Rationale**

Endothelial dysfunction has been described in animal models of chronic inflammation (Urbich and Dimmeler, 2004) and cardiovascular diseases (Anderson *et al.*, 1995; Panza *et al.*, 1990; Quyyumi *et al.*, 1997; Schachinger and Zeiher, 1995; Volpe *et al.*, 1996). During tissue inflammation or injury, the production of cytokines including interleukin-1 (IL-1 $\beta$ ) and interleukin-6 (IL-6) have been reported to contribute to the development of endothelium dysfunction. This dysfunction results in a diminished ability of vessels to modulate tone in response to either endogenous or exogenous vasoactive substances, such as bradykinin and acetylcholine. Endothelial dysfunction is associated with progression of cardiovascular diseases such as hypertension, cerebrovascular diseases, and coronary artery disease (Brunner *et al.*, 2005). Mediators of inflammation, which includes IL-1 $\beta$ , have also been found to upregulate endothelial cell responses to proteinase-activated receptor 2 (PAR<sub>2</sub>) activation (Nystedt *et al.*, 1996). For example PAR<sub>2</sub> activation by PAR<sub>2</sub>-activating peptides (PAR<sub>2</sub>-AP) can induce further cytokine (IL-

6, IL-8) production (Lourbakos *et al.*, 2001) and adhesion molecule expression in endothelial cells (Buddenkotte *et al.*, 2005; Shpacovitch *et al.*, 2004). If activating PAR<sub>2</sub> induces the production of cytokines then PAR<sub>2</sub> activation is expected to lead to endothelial dysfunction.

*In vivo* studies have reported that PAR<sub>2</sub>-APs administered acutely causes a range of effects including hyperalgesia (Vergnolle *et al.*, 2001), increased salivary secretion (Kawabata *et al.*, 2000; Kawabata *et al.*, 2004), and scratching (Shimada *et al.*, 2006), which are effects that would be attributed to localized tissue inflammation. High doses of some PAR<sub>2</sub>-APs have been found to generate non-PAR<sub>2</sub> vascular actions *in vitro*, and thus, provide potential confounding interpretations for *in vivo* studies (McGuire *et al.*, 2002a). In isolated blood vessel assays, nanomolar concentrations of PAR<sub>2</sub>-APs cause vasodilation which is dependent on an intact endothelium and PAR<sub>2</sub> expression (McGuire *et al.*, 2002a; McGuire *et al.*, 2002b; Saifeddine *et al.*, 1996). The PAR<sub>2</sub>-AP 2-furoyl-LIGRLO-NH<sub>2</sub> (2fly) has 30- to 100-times the *in vitro* potency of legacy PAR<sub>2</sub>-APs (SLIGRL-NH<sub>2</sub>) and lacks the non-PAR<sub>2</sub> effects of these compounds in the same assays (McGuire *et al.*, 2004a). Acutely administered intravenous (i.v.) PAR<sub>2</sub>-APs, including 2fly, lowered blood pressures of anaesthetized rodents (Cheung *et al.*, 1998; Damiano *et al.*, 1999; Wang *et al.*, 2010). Decreases in mean arterial blood pressures in response to i.v. 2fly have been replicated in anaesthetized rats by our laboratory (McGuire and Tabrizchi, unpublished data). Acute PAR<sub>2</sub> infusions in humans caused an increase in forearm blood flow and were well-tolerated (Robin *et al.*, 2003). Interestingly, the

vasodilator effects of 2fly and other PAR<sub>2</sub>-APs have been found to persist in resistance arteries under conditions when other endothelium-dependent relaxing agents have reduced efficacy (Kagota *et al.*, 2011; McGuire *et al.*, 2007; Smeda and McGuire, 2007; Smeda *et al.*, 2010). *In vitro* studies have reported a protective role of PAR<sub>2</sub> activation against ischemic reperfusion damage in the coronary vasculature (Napoli *et al.*, 2000). These effects appear to contradict the notion of PAR<sub>2</sub> activation causing endothelial dysfunction. In fact, protection against ischemia, persistent vasodilator activity, and blood pressure lowering effects of PAR<sub>2</sub>-AP would suggest evidence of PAR<sub>2</sub>-AP being useful against the negative effects of endothelial dysfunction.

*Which way, agonist or antagonist, should we target PAR<sub>2</sub> to produce a therapeutic benefit?* Acutely administered small molecule antagonists of PAR<sub>2</sub> have been reported to be effective in rodent models of acute inflammatory diseases, including the use ENMD-1068 in an immune system-induced arthritis model (Kelso *et al.*, 2006). Studies in PAR<sub>2</sub> gene knockout mice (PAR<sub>2</sub><sup>-/-</sup>) indicate gene deficiency for this receptor is protective against several types of tissue inflammation including airway inflammation (Schmidlin *et al.*, 2002), contact dermatitis (Seeliger *et al.*, 2003), and colitis (Lindner *et al.*, 2000). However, there is also evidence to indicate that injury and inflammation responses were increased in PAR<sub>2</sub><sup>-/-</sup>. Increased inflammation was found in mouse pancreatitis (Sharma *et al.*, 2005). Acute focal ischemic brain injury was reported to be higher in PAR<sub>2</sub><sup>-/-</sup> (Jin *et al.*, 2005). In conscious unrestrained PAR<sub>2</sub><sup>-/-</sup>, we reported significantly elevated systolic arterial and pulse pressures compared to their control strain

under baseline conditions (McGuire *et al.*, 2008). Our data were acquired by radiotelemetry, which is the method with the highest resolution for conscious blood pressure measurements. Other earlier studies, that collected hemodynamic data via carotid dwelling catheters in isoflurane-anaesthetized mice, reported no difference between PAR<sub>2</sub><sup>-/-</sup> and control mice (Damiano *et al.*, 1999). A search of the most recent literature (to June 2011) indicates no published studies of the chronic effects of PAR<sub>2</sub>-AP administered *in vivo*.

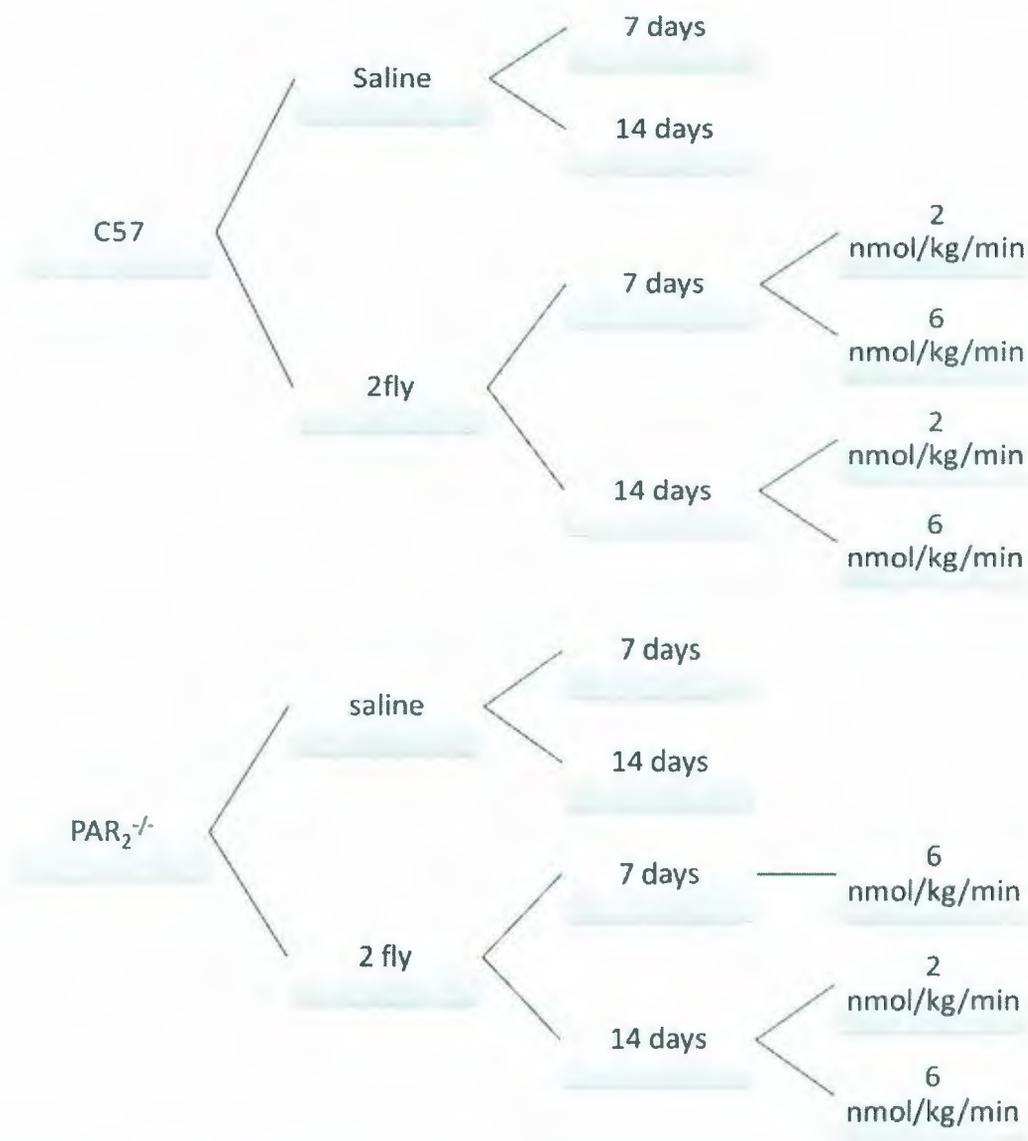
PAR<sub>2</sub> activation *in vivo* may be expected to induce inflammation leading to endothelium dysfunction, and thus, contribute to the development of cardiovascular diseases including hypertension. However, this possible effect does not exclude a time- or dose-dependent hypotensive effect of chronic administered PAR<sub>2</sub>-AP.

### 1.3 Hypotheses and Objectives

This thesis tested two hypotheses. **Hypothesis 1** was that chronic treatment of mice with PAR<sub>2</sub>-AP would induce time- and dose-dependent endothelium dysfunction linked to loss of endothelium-derived NO relaxation; PAR<sub>2</sub>-AP would not cause endothelial dysfunction in PAR<sub>2</sub><sup>-/-</sup>. **Hypothesis 2** was that chronic treatment of mice with PAR<sub>2</sub>-AP would induce time-dependent lowering of blood pressures in normal mice with no effect in PAR<sub>2</sub><sup>-/-</sup>.

To test **Hypothesis 1**, we established a chronic PAR<sub>2</sub>-AP treatment model which comprised administering either of two doses of PAR<sub>2</sub>-AP 2fly (2 nmol/kg/min (low dose, LD) and 6 nmol/kg/min (high dose, HD)) to normal healthy mice (C57BL/6J; C57) and

PAR<sub>2</sub>-deficient (B6.Cg-F2r11<sup>tm1Mslb</sup>/J; PAR<sub>2</sub><sup>-/-</sup>) for 7 and 14 days by subcutaneous infusions via micro-osmotic pumps (Figure 1.1).



**Figure 1.1 Experimental design for mice treatment.** Abbreviations: C57, C57BL/6J mice; PAR<sub>2</sub><sup>-/-</sup>, B6.Cg-F2r11<sup>tm1Mslb</sup>/J mice; 2fly, 2-furoyl-LIGRLO-NH<sub>2</sub>; saline, 0.9% NaCl; 2 nmol/kg/min, low dose (LD) 2fly; and 6 nmol/kg/min, high dose (HD) 2fly.

The nitric oxide-mediated smooth muscle relaxation by endothelium-dependent (2fly, acetylcholine, calcium ionophore (A23187)) and –independent (nitroprusside) agonists in aortas from these mice were recorded while contracted by a thromboxane A<sub>2</sub> agonist under isometric tension conditions in myographs. **Objective 1** was to characterize the dose and time effects of *in vivo* PAR<sub>2</sub>-AP treatment on the subsequent vascular reactivity of aortas as a measurement of endothelial and smooth muscle cell health. **Objective 2** was to characterize the nitric oxide component of relaxations by measuring the agonist relaxation activity in chronic PAR<sub>2</sub>-AP treated mice using pharmacological inhibitors of endothelial nitric oxide synthase (N $\omega$ -nitro-L-arginine-methyl ester, L-NAME) and cyclooxygenases (indomethacin). Based on initial experiments, it was apparent that chronic PAR<sub>2</sub>-AP treatments attenuated the aortas relaxations induced by 2fly, ACh and nitroprusside in C57. **Objective 3** was to identify the possible mechanisms underlying the attenuated relaxations by PAR<sub>2</sub>-AP. Western blotting of aortic proteins and immunohistochemical staining of aortas for PAR<sub>2</sub> were used to measure the expression levels of endothelial NO synthase (eNOS), soluble guanylyl cyclase (sGC), cyclooxygenases isoforms -1 and -2 (COX-1, COX-2), and PAR<sub>2</sub> to investigate the contributions of these components in attenuated relaxations.

To test **Hypothesis 2**, we used the chronic PAR<sub>2</sub>-AP treatment model described above. **Objective 4** was to test whether high dose PAR<sub>2</sub>-AP administered chronically lowered blood pressures in mice. To do this we recorded continuously the blood pressures and locomotor activity by radiotelemetry while administering the high dose PAR<sub>2</sub>-AP to

mice.

From these studies, we expected to determine the effects of chronic treatment with PAR<sub>2</sub>-AP on the endothelium function of mouse aortas and on the blood pressures, heart rates, and locomotor activities of mice.

## Chapter 2: Literature Review

### 2.1 Proteinase-activated receptors (PARs)

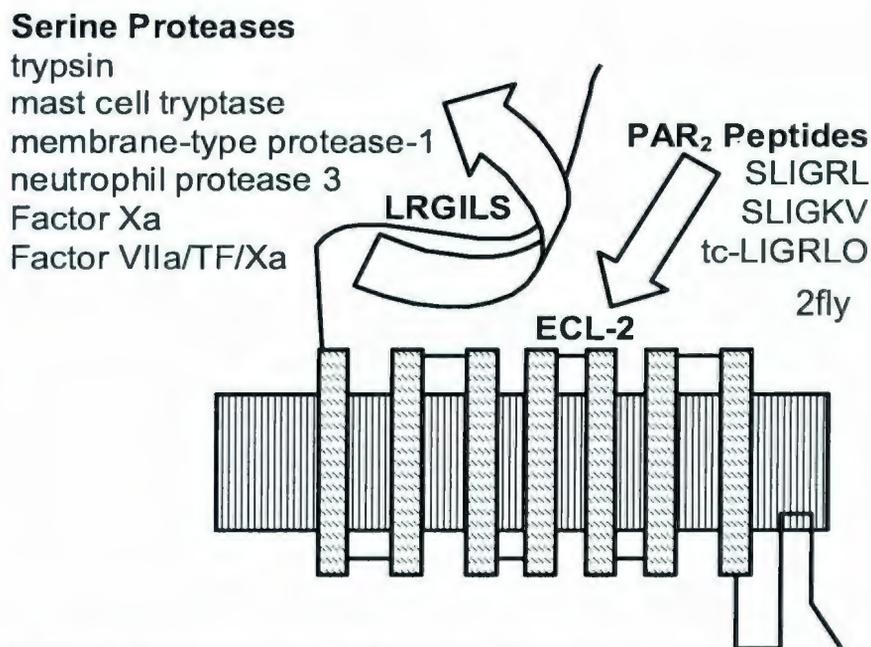
Proteinase-activated receptors are a class of seven transmembrane domain G-protein coupled receptors, which consists of a family of 4, numbered 1 to 4 according to order of discovery (reviewed in Hollenberg, 2003). In the cardiovascular system, PAR are found on platelets (PAR<sub>1</sub>, PAR<sub>3</sub> and PAR<sub>4</sub>; Kahn *et al.*, 1998; Vu *et al.*, 1991), endothelial cells (PAR<sub>1</sub>, PAR<sub>2</sub>, and PAR<sub>3</sub>; D'Andrea *et al.*, 1998; Hamilton *et al.*, 2002), smooth muscle cells (PAR<sub>1</sub> and PAR<sub>2</sub>; D'Andrea *et al.*, 1998; Hamilton *et al.*, 2002), cultured cardiomyocytes (PAR<sub>1</sub>, PAR<sub>2</sub>, and PAR<sub>4</sub>; Hamilton *et al.*, 2002, Ide *et al.*, 2007, and Sabri *et al.*, 2003), megakaryocytes (PAR<sub>3</sub> and PAR<sub>4</sub>; Ishihara *et al.*, 1997 and Kahn *et al.*, 1998), leukocytes (PAR<sub>2</sub>; Dery *et al.*, 1998) and fibroblasts (PAR<sub>1</sub>; Connolly *et al.*, 1996).

The normal structure of PAR conceals a tethered ligand that is exposed by serine proteinases cleaving the N-terminal domain of PAR. Table 2.1 contains the N-terminal amino acid sequences of the revealed tethered ligands in mice, rats, and humans. The N-terminus binds to a region of extracellular loop 2, which induces a conformational change in the receptor that couples with activation of several possible G-proteins (reviewed in

<b>Receptor</b>	<b>Revealed tethered ligand sequence</b>
PAR <sub>1</sub>	(human) SFLLRN... (rat, mouse) SFFLRN...
PAR <sub>2</sub>	(human) SLIGKV... (rat, mouse) SLIGRL...
PAR <sub>3</sub>	(human) TFRGAP... (mouse) SFNGGP...
PAR <sub>4</sub>	(human) GYPGQV... (mouse) GYPGKF... (rat) GFPGKP...

**Table 2.1 Tethered ligand sequences from human, rat, and mouse for each member of the PAR family.** Modified from Hansen *et al.*, 2008.

Macfarlane *et al.*, 2001). Selectivity for the activation of PARs amongst serine proteases (a superfamily of enzymes) has been identified: for example, thrombin activates PAR<sub>1</sub>, PAR<sub>3</sub>, and PAR<sub>4</sub>, but not PAR<sub>2</sub> (MacFarlane *et al.*, 2001). PAR-activating peptides (PAR-AP) mimic the tethered ligand sequence and so are substituted as more practical pharmacological tools than enzymes (Dery *et al.*, 1998; Hollenberg *et al.*, 1997; Hollenberg *et al.*, 1999). Figure 2.1 illustrates these two mechanisms for PAR<sub>2</sub> activation: 1. Cleaving the N-terminus produces PAR<sub>2</sub>-tethered ligand, and 2. binding of extracellular loop 2 by PAR<sub>2</sub>-AP.



**Figure 2.1 Illustration comparing PAR<sub>2</sub> activation by enzymes versus PAR<sub>2</sub>-AP.**

Modified from McGuire (2004). Used with author's permission.

## 2.2 PAR<sub>2</sub>-activating peptides

Several of the more common PAR-APs are listed in Table 2.2. 2-furoyl-LIGRLO-NH<sub>2</sub> (2fly) has proven to be one of the most potent and specific agonists that have been purposefully designed to target PAR<sub>2</sub>. 2fly is 10 to 300-times more potent than SLIGRL-NH<sub>2</sub>, the native amino acid sequence of the exposed region in rats and mice (Table 2.2) (McGuire *et al.*, 2004a). The substitution of serine by a furoyl group and the addition of ornithine to the carboxy terminus of SLIGRL contribute to increased potency and a resistance to aminopeptidases. In total, 2fly is a more effective PAR<sub>2</sub>-AP compared to

what we refer to as legacy PAR<sub>2</sub>-AP.

PAR <sub>1</sub>	PAR <sub>2</sub>	PAR <sub>3</sub>	PAR <sub>4</sub>
SFLLRN-NH <sub>2</sub>	SFLLRN-NH <sub>2</sub>	TFRGAP <sup>a</sup>	GYPGQV-NH <sub>2</sub>
TFLLR-NH <sub>2</sub>	SLIGKV-NH <sub>2</sub>		GYPGKF-NH <sub>2</sub>
TFRIFD	SLIGRL-NH <sub>2</sub>		AYPGKF-NH <sub>2</sub>
	transcinnamoyl-LIGRLO-NH <sub>2</sub>		
	2-furoyl-LIGRLO-NH <sub>2</sub>		

**Table 2.2 PAR-activating peptides.** Peptide sequences are abbreviated by the internationally accepted biochemical nomenclature standard using the 1 letter code for each amino acid. Exceptions, NH<sub>2</sub> = amide functional group. Though not listed separately, it is common to find that studies have used the free carboxylic acid forms, which have 10-times less potency than the amides. <sup>a</sup> Although this is the reference for the tethered ligand sequence, it has not been found to activate PAR<sub>3</sub>.

### 2.3 Cardiovascular actions of PAR<sub>2</sub>-APs

A potentially promising therapeutic activity of PAR<sub>2</sub>-APs is that these compounds can produce endothelium-dependent relaxation of vascular smooth muscle cells (Al-Ani *et al.*, 1995). In acute *in vivo* studies PAR<sub>2</sub>-AP caused a reduction in blood pressure without increasing heart rate in anaesthetized rats (Emilsson *et al.*, 1997) and mice (Cheung *et al.*, 1998) using SLIGRLETQPPI and SLIGRL-NH<sub>2</sub> respectively. It was reported by McLean *et al.* (2002) that PAR<sub>2</sub> activation was protective against myocardial

ischemia and reperfusion injury. This protection occurred because PAR<sub>2</sub>-AP infusion increased coronary perfusion despite being unresponsive to acetylcholine under these conditions (McLean *et al.*, 2002). Robin *et al.* (2003) administered i.v. SLIGKV-NH<sub>2</sub> to healthy volunteers while measuring blood flow in the forearm. They reported no adverse effects and that SLIGKV-NH<sub>2</sub> increased blood flows. These increases by SLIGKV-NH<sub>2</sub> were reduced (26%) by pretreatment by N<sup>G</sup>-methyl-L-arginine and were reduced even more by combining the later with aspirin.

In various animal models of human diseases, PAR<sub>2</sub> mediated vasodilation is preserved despite other endothelium-dependent vasodilators being less effective. In genetic hypertensive mice (BPH/2) relaxation of small mesenteric arteries by PAR<sub>2</sub>-AP were only slightly reduced (6%) when compared to normotensive mice (BPN/3) (McGuire *et al.*, 2007). In contrast, relaxations by acetylcholine and bradykinin in BPH/2 were significantly reduced by 25-50% compared to BPN/3 (McGuire *et al.*, 2007). This preservation of PAR<sub>2</sub> function in the small calibre arteries was attributed to an endothelium-dependent hyperpolarization mechanism. In basilar (Sobey *et al.*, 1999) and pulmonary arteries (Wanstall and Gambino, 2004), the preserved PAR<sub>2</sub> relaxations were nitric oxide (NO) mediated in SHR and pulmonary hypertensive rats, respectively. Similar to the findings by McGuire *et al.* (2007), stroke prone hypertensive rats (SHR) displayed reduced middle cerebral artery vasodilation by bradykinin and A23187 while 2fly-induced vasodilation remained unchanged (Smeda and McGuire, 2007). According to PAR<sub>2</sub> immunostaining of middle cerebral arteries there was no apparent change in

distribution of PAR<sub>2</sub> expression (Smeda *et al.*, 2010). When taken together, these studies reveal that PAR<sub>2</sub>-AP could play a number of cardioprotective roles. The acute lowering of arterial blood pressures is one protective role. The maintenance of the capacity for endothelium-dependent relaxation despite reduction in effectiveness of other vasodilators in disease models is a second protective role.

#### **2.4 *In vivo* effects of PAR<sub>2</sub>-AP link with inflammation and immunity**

PAR<sub>2</sub> activation *in vivo* can cause both anti-inflammatory and pro-inflammatory effects as well as change expression of molecules associated with immune mechanisms. Anti-inflammatory effects have been measured by acutely administering *in vitro* and *in vivo* PAR<sub>2</sub>-APs. One early *in vitro* study of PAR<sub>2</sub>-APs infused SLIGRL-NH<sub>2</sub> in a rat model of myocardial ischemia reperfusion injury (isolated perfused working hearts). This caused an increase in myocardial contractile recovery and decreased oxidative stress from free radicals during reperfusion in the ischemic risk zone (Napoli *et al.*, 2000). In the respiratory system, intranasal administered SLIGRL inhibited antigen-induced hyper-reactivity and infiltration of eosinophils in the airway (De Campo and Henry, 2005). SLIGRL administered *in vivo* also increased prostaglandin E<sub>2</sub> levels in the bronchiolar lavage (a mechanism in the lung that reduces inflammation by reducing inflammatory molecule recruitment (Lan *et al.*, 2001; Vancheri *et al.*, 2004)) in the absence of any inhibitors. When PAR<sub>2</sub>-AP was co-administered with indomethacin (blocking prostaglandin E<sub>2</sub> production) the allergy hyper-responsiveness returned (De Campo and Henry, 2005). Intrarectal administered SLIGRL-NH<sub>2</sub> was found to protect against

experimental colitis that had been induced by exposure to trinitrobenzene sulfonic acid (Fiorucci *et al.*, 2001). This protection by PAR<sub>2</sub>-AP was described by increased macroscopic and histological scores and reduced level of T helper 1 type cell cytokines (Fiorucci *et al.*, 2001). These studies demonstrate the ability of PAR<sub>2</sub> to elicit anti-inflammatory effects. The latter two studies also display differences in the modulation of immune mechanisms. The activation of PAR<sub>2</sub> caused changes in the amount of mediators of the immune response, an increase in prostaglandin E<sub>2</sub> (an anti-inflammatory effect in the lungs) and a decrease in T helper 1 type cell cytokines.

*In vivo* administered PAR<sub>2</sub>-AP can cause pro-inflammatory effects. Injection of SLIGRL-NH<sub>2</sub> into rat paws caused oedema resulting from increased vascular permeability (Kawabata *et al.*, 1998; Vergnolle *et al.*, 1999). The oedema in these rats was characterized as being independent of mast cell activation and of the production of prostanoids and NO. These features of inflammation were demonstrated in hind paw oedema using compound 48/80 (depletes mast cells), cromolyn (a mast cell stabilizer), indomethacin, and L-NAME, respectively (Vergnolle *et al.*, 1999). Increased inflammatory response described by joint swelling and synovial vasodilation has also been reported to occur in mouse knee joints that had been administered either SLIGRL-NH<sub>2</sub> or 2-furoyl-LIGKV-OH (Ferrell *et al.*, 2003). Local intracolonic administration of SLIGRL-NH<sub>2</sub> caused inflammation as described by increased wall thickness and macroscopic damage score, caused increased tumor necrosis factor- $\alpha$ , IL-1 $\beta$ , and interferon- $\gamma$  mRNA expression (increase in T-helper 1 cells) and caused increased

epithelial permeability (Cenac *et al.*, 2002). PAR<sub>2</sub>-AP 2fly administered to rats prior to intestinal irradiation exacerbated the tissue injury at early time points following exposure (Wang *et al.*, 2010). These studies show that PAR<sub>2</sub> activation *in vivo* has potential to increase pro-inflammatory effects at multiple sites and has been associated with immunity regulated by T-helper 1 cells.

## 2.5 PAR<sub>2</sub> antagonists

To understand the consequences of PAR<sub>2</sub> activation more clearly, PAR<sub>2</sub> antagonists would be of great use. Researchers have synthesized antagonists of PAR<sub>1</sub> that have been characterized by their ability to inhibit both the initial transient global cytosolic calcium signal and endothelium-mediated relaxation (reviewed in Ahn *et al.* 2003). However, there has been limited success in developing an antagonist to PAR<sub>2</sub>. One approach used to develop PAR<sub>2</sub>-antagonist compounds was functional screening of peptides comprised of the reversed amino acid sequence of the PAR activating peptides. Al-ani *et al.* (2002) attempted this approach for both PAR<sub>1</sub> and PAR<sub>2</sub> using FSLLRY-NH<sub>2</sub> and LSIQRL-NH<sub>2</sub> respectively. These peptides were previously described as having no PAR agonist activity (Al-ani *et al.*, 1999). FSLLRY-NH<sub>2</sub> and LSIQRL-NH<sub>2</sub> blocked trypsin activation of PAR<sub>2</sub>, but did not block SLIQRL-NH<sub>2</sub> mediated activation of calcium signaling in Kirsten virus-transformed kidney cells or relaxation of rat aorta (Al-ani *et al.*, 2002). Other approaches to develop inhibitors of PAR activities include peptidomimetic molecules (Ahn *et al.*, 2003), pepducins (Kaneider *et al.*, 2007), small interfering ribonucleic acid sequences (siRNA), and monoclonal antibodies (Kelso *et al.*,

2006).

Mimetic molecules for PAR<sub>1</sub> inhibition are compounds that resemble the chemistry of the same binding motif as the activating amino acid sequences, the template being a 6-aminoindole ring. One such antagonist is RWJ-58259, which binds with high affinity and inhibits PAR<sub>1</sub> mediated platelet aggregation (Ahn *et al.*, 2003). The inhibitor actions of PAR<sub>1</sub> small-nonpeptide inhibitors including pyrroloquinazoline analogs, benzimidazole derivatives, and himbacine analogs have also been described (Ahn *et al.*, 2003). Generally, pepducins can have either agonist or antagonist activity by interacting intracellularly with the G-protein coupled pathways. These compounds have been successfully employed as agonists to both PAR<sub>1</sub> (Kaneider *et al.*, 2007) and PAR<sub>2</sub> (Covic *et al.*, 2002; Kaufmann *et al.*, 2009), but not as PAR antagonists. siRNAs, antibodies (B5 antibody specifically), and *N*1-3-methylbutyryl-*N*4-6-aminohexanoyl-piperazine (ENMD-1068) have been successfully employed to partially inhibit PAR<sub>2</sub> activation (Kelso *et al.*, 2006). siRNAs reduced the amount of knee joint swelling after cytokine induction. The B5 antibody serum also reduced knee joint swelling in mice after induction of inflammation via carrageenan/kaolin (Kelso *et al.*, 2006). ENMD-1068 reduced calcium signaling in Lewis lung carcinoma cells mediated by SLIGKV-NH<sub>2</sub>, but had no effect on trypsin activation in these cells (Kelso *et al.*, 2006), and thus, was a partial antagonist.

In the past two years there has finally been some progress made in discovery of small molecule inhibitors of PAR<sub>2</sub>. One study, by Kanke *et al.* (2009) described two new peptidomimetic antagonists of PAR<sub>2</sub> (K-12940 and K-14585). Both antagonists reduced

SLIGKV-induced calcium influx in primary human keratinocytes and inhibited competitively the specific binding of [<sup>3</sup>H]-2-furoyl-LIGRL-NH<sub>2</sub> to the cell membrane (Kanke *et al.*, 2009). Competitive inhibition of SLIGRL-induced relaxation of rat aorta was reported with K-14585 (Kanke *et al.*, 2009). The most recent study, by Barry *et al.* (2010), described the first compound (GB83) to inhibit PAR<sub>2</sub> activation via proteinases and by synthetic peptides (2fly) at low concentrations. GB83 was shown to inhibit PAR<sub>2</sub> induced intracellular calcium release in a colon cancer cell line in a dose dependent manner with full potency at μM concentrations.

It has taken many years to develop an antagonist of PAR<sub>2</sub> that has the ability to inhibit activation by proteinases and synthetic peptides. It is expected that GB83 should prove to be very useful to further describe the actions of PAR<sub>2</sub> and the consequences of blocking the receptor.

## **2.6 PAR<sub>2</sub> knockout mice**

Prior to discovery of pharmacological inhibitors of PAR<sub>2</sub>, transgenic PAR<sub>2</sub><sup>-/-</sup> mice have been used to investigate the *in vivo* role of PAR<sub>2</sub> in various experimental models of diseases. Several strains of PAR<sub>2</sub><sup>-/-</sup> mice have been used to investigate the cardiovascular actions of PAR<sub>2</sub> (Damiano *et al.*, 1999; McGuire *et al.*, 2002a; McGuire *et al.*, 2008) and inflammatory models of disease (Cenac *et al.*, 2002; Ferrell *et al.*, 2003; Kelso *et al.*, 2006; Lindner *et al.*, 2000; Schmidlin *et al.*, 2002; Seeliger *et al.*, 2003).

Cardiovascular phenotype characteristics present in PAR<sub>2</sub><sup>-/-</sup> include higher systolic arterial pressures and pulse pressures compared with C57 (PAR<sub>2</sub><sup>+/+</sup>) under baseline

conditions when measured by radiotelemetry (McGuire *et al.*, 2008). These mice have also been used to demonstrate that hypotension produced by acute i.v. administered SLIGRL-NH<sub>2</sub> in wild type mice was due to PAR<sub>2</sub> expression (Damiano *et al.*, 1999).

There are differences in PAR<sub>2</sub><sup>-/-</sup> responses in various models of inflammation which creates some uncertainty about the pathophysiological role that may be played by PAR<sub>2</sub>. PAR<sub>2</sub><sup>-/-</sup> mice are protected from airway inflammation (Schmidlin *et al.*, 2002), contact dermatitis (Seeliger *et al.*, 2003), and colitis (Lindner *et al.*, 2000). The inflammatory response is substantially less in mouse knee joints of PAR<sub>2</sub><sup>-/-</sup> compared to their wild type counterpart after adjuvant induced arthritis (Ferrell *et al.*, 2003). In this arthritis model PAR<sub>2</sub><sup>-/-</sup> mice had lowered swelling compared to wild type. Intracolonic administration of SLIGRL-NH<sub>2</sub> caused little change in inflammation of PAR<sub>2</sub><sup>-/-</sup> mice as compared to PAR<sub>2</sub><sup>+/+</sup> mice (Cenac *et al.*, 2002). PAR<sub>2</sub><sup>+/+</sup> had increased wall thickness and macroscopic damage score, increased tumor necrosis factor- $\alpha$ , IL-1 $\beta$ , and interferon- $\gamma$  mRNA expression (increase in T-helper 1 cells) and increased permeability (Cenac *et al.*, 2002). In general, PAR<sub>2</sub><sup>-/-</sup> responses to immune system action are lower than PAR<sub>2</sub><sup>+/+</sup>, but there is contradictory evidence that indicates that injury and inflammatory responses in some cases were increased in PAR<sub>2</sub><sup>-/-</sup>.

Increased inflammation was observed after acute focal ischemic brain injury as PAR<sub>2</sub><sup>-/-</sup> mice compared to their counterparts had an increased infarct volume (Jin *et al.*, 2005). In pancreatitis there seems to be different effects that are dependent on the mechanism of inducing inflammation. Induction of pancreatitis by a supramaximal

caerulein stimulation caused increased inflammation in PAR<sub>2</sub><sup>-/-</sup> mice (Sharma *et al.*, 2005) whereas the inflammation induced by retrograde administration of bile salts in the pancreatic duct was reduced in PAR<sub>2</sub><sup>-/-</sup> (Laukkarinen *et al.*, 2008). These findings are evidence that PAR<sub>2</sub><sup>-/-</sup> mice may exhibit different outcomes, sometimes opposite, depending on the tissues and experimental model studied. For our purposes it is important to know that PAR<sub>2</sub><sup>-/-</sup> can exhibit different inflammatory responses when stimulated.

## **2.7 Endothelium-dependent relaxation mechanisms**

An understanding of vasodilator mechanisms similar to those produced by PAR<sub>2</sub> activation, such as endothelium-dependent relaxation by cholinergic agonist acetylcholine and calcium ionophore A23187, is useful to designing studies to characterize potential signal transduction mechanisms underlying PAR<sub>2</sub> responses.

In what are now considered classic *in vitro* experiments, the neurotransmitter acetylcholine was found to relax precontracted rabbit aortas (Furchgott and Zawadzki, 1980). Relaxation was dependent on the presence of intact endothelial cells because when inner surfaces of rabbit aortas were damaged by rubbing, relaxation did not occur (Furchgott and Zawadzki, 1980). These fundamental observations led to the co-award of the 1998 Nobel Prize in Medicine to Furchgott, Ignarro, and Murad; the work of the latter two contributed to the identification of (NO) being the mediator of this endothelium-dependent relaxation and the role of soluble guanylyl cyclase in signal transduction, respectively (SoRelle, 1998).

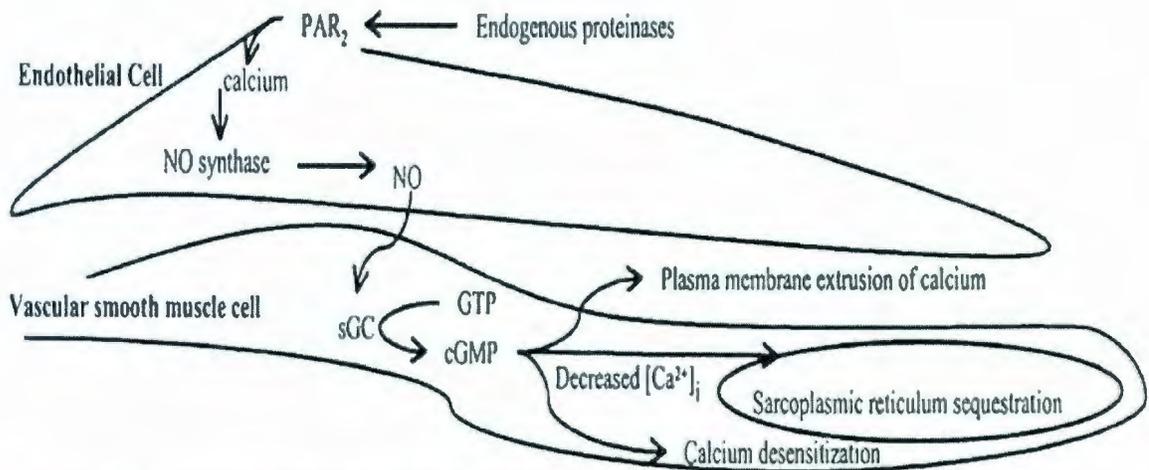
Acetylcholine activates the type 3 muscarinic receptor (M3) found on endothelial

cell plasma membranes (Dauphin and Hamel, 1990). M3 cholinoreceptor is a classic seven transmembrane domain G-protein coupled receptor. Briefly, activation of M3 receptors causes  $G\alpha_q$  to exchange GDP for GTP.  $G\alpha_q$  is released from its  $G\beta\gamma$  subunit which acts as the signal transduction molecule leading to activation of phospholipase C. Phospholipase C cleaves phosphatidylinositol-4, 5-bisphosphate into inositol triphosphate and diacylglycerol (Noh *et al.*, 1995). Inositol triphosphate binds to its nominal receptor on the endoplasmic reticulum that causes a release of stored  $Ca^{2+}$  into the cytosol of endothelial cells (Noh *et al.*, 1995).  $Ca^{2+}$  binds to calmodulin to activate endothelial nitric oxide synthase (eNOS) (Matsubara *et al.*, 1996). NO synthases catalyse the oxidation of L-arginine to L-citrulline while producing diffusible free radical gas NO (Kwon *et al.*, 1990). NO diffuses into the smooth muscle cells where it binds to and activates soluble guanylyl cyclase, which converts GTP to cGMP. The accumulation of cGMP leads to activation of cyclic GMP-dependent protein kinases and subsequent phosphorylation of various substrates linked to the regulation of  $Ca^{2+}$  including those mediating sequestration by the sarcoplasmic reticulum (Twort and Breemen, 1988),  $Ca^{2+}$  desensitization (Stull *et al.*, 1990; Tansey *et al.*, 1992), and plasma membrane  $Ca^{2+}$  extrusion from the smooth muscle cell (Popescu *et al.*, 1985).

A23187 is a calcium ionophore that has blood vessel relaxant activity, that is dependent (in a concentration dependent manner) on the presence of an endothelium layer (Furchgott, 1983). It has a different mechanism of action than acetylcholine. A23187 forms pores in the membrane of endothelial cells that allow the entry of  $Ca^{+2}$  into the

cells (Reed and Lardy, 1972). It is proposed that this stimulates the production of NO, which follows the same pathway as NO derived by eNOS, to cause relaxation through sGC.

PAR<sub>2</sub>-AP mediated endothelium-dependent relaxation of large calibre arteries occurs by a mechanism which resembles that underlying the typical acetylcholine- and A23187-induced relaxations. In large arteries NO is the mediator of the PAR<sub>2</sub> signal transduction mechanism (Figure 2.2). In small resistance calibre arteries, endothelium agonists including PAR<sub>2</sub>-AP (McGuire *et al.*, 2002; McGuire *et al.*, 2004a), acetylcholine and A23187 do not necessarily require NO to cause vasodilation. In the presence of NOS inhibitors, for example L-NAME, SLIGRL-NH<sub>2</sub> and other PAR<sub>2</sub>-APs induce the relaxation of small mesenteric arteries contracted by a vasoconstricting agonist (McGuire, 2002). These responses are mediated by endothelium-dependent hyperpolarization (EDH) of vascular smooth muscle, which involves activation of small- and intermediate-conductance Ca<sup>2+</sup>-activated K<sup>+</sup> channels on the endothelium (McGuire *et al.*, 2002a; McGuire *et al.*, 2002b; McGuire *et al.*, 2004a; McGuire *et al.*, 2004a). This alternate EDH cascade may provide a mechanism for vasodilation of arteries in disease states when NO is limited.



**Figure 2.2 Vascular smooth muscle relaxation by PAR<sub>2</sub> activation via endothelial-derived NO.** Used with the author's permission (McGuire, 2004).

## 2.8 Endothelium-independent nitrovasodilators

Nitroprusside initiates its vasodilator action upon spontaneous release of NO (Rao and Cederbaum, 1995). Thus, nitroprusside provides an exogenous source of diffusible NO that causes smooth muscle to relax. The mechanism of action of nitroprusside bypasses the endothelium and the activation of eNOS, but still involves activation of soluble guanylyl cyclase and cyclic GMP-dependent protein kinase activation. Nitroprusside is frequently used as a tool for comparing relaxation by endothelium-dependent and -independent mechanisms.

## 2.9 Non-hemodynamic effects of PAR<sub>2</sub>-AP on endothelial cells

There has been much work performed on endothelial cells to try to describe how PAR<sub>2</sub> mediates its actions within *in vivo* and *in vitro* systems. These studies have found PAR<sub>2</sub>-APs also have many non-hemodynamic effects on endothelial cells, including

stimulating the production of pro-inflammatory molecules and other mediators of the innate immune system. Activation of PAR<sub>2</sub> also increased the release of prostanoids and cytokines (IL-6 and IL-8) in epithelial and non-epithelial cells (Lourbakos *et al.*, 2001). PAR<sub>2</sub> activation in cell lines is partly linked to the NFκB pathway (Buddenkotte *et al.*, 2005; Goon Goh *et al.*, 2008; Kanke *et al.*, 2001; Macfarlane *et al.*, 2005) involved in the regulation of IL-8 production (Yoshida *et al.*, 2007). Also the activation of p38 MAP kinase and NFκB by PAR<sub>2</sub>-AP in human umbilical vein endothelial cells has been reported (Ritchie *et al.*, 2007). PAR<sub>2</sub> expression can be upregulated by tumor necrosis factor-α, IL-1β, and lipopolysaccharide in human umbilical vein endothelial cells (Nystedt *et al.*, 1996). Together these observations imply evidence linking PAR<sub>2</sub> to pro-inflammatory actions of endothelial cells.

## **2.10 Methods for assessment of endothelial dysfunction**

In a clinical setting there are several technical methods to assess endothelial dysfunction. The typical approach has involved recording hemodynamic responses by acetylcholine, bradykinin and or endothelium-independent nitrovasodilators. It is proposed that an attenuated responsiveness to all of these drugs is enough to demonstrate endothelial dysfunction. For example, quantitative coronary angiography (Cox *et al.*, 1989) is employed to visualize blood vessels vasodilations by these agonists (Schachinger *et al.*, 2000). Alternate methods have been proposed, which include recording the coronary arteries responses to cold pressor testing (Schindler *et al.*, 2003) and flow-mediated vasodilation of large arteries of the forearm vascular bed (Perticone *et al.*, 2001)

or microvasculature (skin microcirculation) using laser Doppler techniques (Deanfield *et al.*, 2005). Another minimally invasive test is to observe the blood pressure (BP) changes occurring during reactive hyperemia using ultrasound and a BP cuff (Celermajer *et al.*, 1992). The premise behind following reactive hyperemia is that in patients with normal vascular function blood flow increases after occlusion, but in patients with endothelial dysfunction the vessel of interest does not relax to the same extent to permit an increase in blood flow (hyperemia). In line with the increasing clinical trend to measure molecular markers of disease (biomarkers) there are multiple markers that have been proposed to assess endothelial dysfunction in humans, which include IL-6, tumor necrosis factor- $\alpha$ , and C reactive protein (Deanfield *et al.*, 2005).

*In vitro* experiments have been performed on arteries isolated from gluteal tissue of human patients. There was reported in these studies a good correlation to the degree of flow-mediated dilation of the patient's brachial artery (Endemann and Schiffrin, 2004). Most *in vitro* research exploring mechanisms of endothelial dysfunction has been performed using animal models for ease of access and range of disease models available. For example, isolated vessels from rodents have been tested for effectiveness of acetylcholine to cause vasodilation under different conditions or stages of disease. Specific models include: spontaneously hypertensive rats (Luscher, 1988; Luscher, 1989), third order mesenterics from the two-kidney one-clip hypertension model in rats (Dohi *et al.*, 1991), angiotensin II hypertension model in rats (Rajagopalan *et al.*, 1996), and diabetic models in rats and rabbits (Cameron and Cotter, 1992; Tesfamariam *et al.*, 1989).

The effectiveness of acetylcholine is also reduced in mice models including hyperhomocystinemia (Viridis *et al.*, 2003). Endothelial dysfunction associated with cytokine production (tumor necrosis factor- $\alpha$  and IL-1B) derived from chronic PAR<sub>2</sub> activation has yet to be determined.

## **Chapter 3: Materials and Methods**

### **3.1 Animal Ethics**

The procedures on mice were approved by the Institutional Animal Care Committee of Memorial University in accordance with the guidelines and principles of the Canadian Council on Animal Care.

### **3.2 Materials**

2fly (PAR<sub>2</sub>-AP) and TFLLR-NH<sub>2</sub> (PAR<sub>1</sub>-AP) were purchased from Peptides International (Louisville, KY). Antibodies SC-2020 (COX-2 secondary antibody), SC-1745 (COX-2 primary antibody), SC-25778 (GAPDH-FL primary antibody), and SC-13504 (PAR<sub>2</sub> primary antibody, (SAM-11)) were purchased from Santa Cruz Biotechnology. Antibodies labeled 160109 (COX-1 primary antibody), and 10004301 (COX-1 and GAPDH-FL secondary antibody) were purchased from Cedarlane (Burlington, ON). Antibodies for eNOS were purchased from BD Transduction Laboratories (primary antibody, 610296) and Vector Laboratories (secondary antibody, PI-2000). Antibodies for sGC were purchased from Abcam (primary antibody, ab5033) and Vector Laboratories (secondary antibody, PI-1000). Oligonucleotide primers for genotyping were purchased from Eurofins MWG Operon (Huntsville, AL). Sybr® Safe

was purchased from Invitrogen (Burlington, ON). For PCR experiments, Taq polymerase, MgCl<sub>2</sub>, DNase-free water and 10 x PCR buffer were purchased from Bio Basic Inc. (Ontario, Canada). Fluorescein isothiocyanate (FITC)-conjugated AffiniPure goat anti-mouse IgG (115-095-003) was purchased from Jackson ImmunoResearch Laboratories (West Grove, PA, USA). All other chemicals were purchased from Sigma Aldrich Canada (Oakville, ON).

### 3.3 Mice

C57BL/6J (C57) and homozygous B6.Cg-*F2r11<sup>tm1Mslb</sup>*/J (PAR<sub>2</sub><sup>-/-</sup>) were obtained from The Jackson Laboratory (Bar Harbor, ME). Three PAR<sub>2</sub><sup>-/-</sup> breeding pairs were used to generate an initial colony. C57 mice were purchased at intervals to age-match the PAR<sub>2</sub><sup>-/-</sup> used in experiments. Male mice (12 to 20 weeks of age) were used in all experiments. Mice were housed within a specific-pathogen free barrier facility until used for experiments, and thereafter, mice were housed in a room dedicated for the main use of radiotelemetry recording. Room temperatures, humidity and light cycles were controlled by Animal Care Services in the Health Sciences Centre, but were monitored routinely for seasonal or unexpected (power blackouts) variations.

### 3.4 Breeding Protocol

The colony of PAR<sub>2</sub><sup>-/-</sup> mice was started with three founding pairs from different parents. These breeding pairs produced about one litter of offspring every three to four weeks. Litter size varied from one to seven offspring. Litters were weaned on day 21 after birth. The litters from the pairs of breeders were then bred together to establish a stable

colony. The colony number was maintained while ensuring there was no breeding between relatives at least as far back as two generations. Eighteen months after the start of breeding the first pairs of PAR<sub>2</sub><sup>-/-</sup>, the rate of colony growth appeared to slow. A decision was made to reestablish the PAR<sub>2</sub><sup>-/-</sup> by backcrossing to C57 followed by breeding heterozygotes. Four pairs of female PAR<sub>2</sub><sup>-/-</sup> of different family lines were mated to male C57 to generate first familial (F1) generations of heterozygote mice (PAR<sub>2</sub><sup>+/-</sup>). These PAR<sub>2</sub><sup>+/-</sup> from each pair were then crossbred (using both males and females from each breeding pair in combination) to create second familial (F2) generations of PAR<sub>2</sub><sup>-/-</sup>, PAR<sub>2</sub><sup>+/-</sup>, and C57 littermates. All mice from heterozygote crosses were genotyped to determine identity using tail clips.

### 3.5 Genotyping

Mice were genotyped using a modification of the supplier's recommended protocol (Jackson Laboratory, Bar Harbor, ME). Dideoxyribonucleic acid (DNA) extraction procedure entailed heating a mouse tail clipping (5 mm length) in a 500 µl solution of 50 mM NaOH for 1 h, cooling to room temperature, adding 50 µl TrisHCl (pH 7.5) followed by mixing and centrifugation at 10,000 x g for 2 min. The supernatant containing DNA was stored at -20 °C. DNA concentration was determined using the NanoDrop 1000 spectrophotometer (Fisher Scientific), which was calculated by the measured absorbance at 260 nm ( $A_{260\text{nm}}$ ) by nucleic acids.

Polymerase chain reactions using 2 primer sets and a reaction mixture was used to amplify DNA. When paired correctly and at the optimal cycling conditions these primers

amplified the portions of DNA that were of interest (Appendix A). The reaction mixture amplified both a portion of the *par2* exon and the neomycin gene present in the PAR<sub>2</sub><sup>-/-</sup> mice. This approach differed from the supplier as our protocol used IMR 5332 as one of the primers while Jackson Laboratories used IMR 7415 to amplify this region. The neomycin gene insert was introduced during the derivation of the PAR<sub>2</sub><sup>-/-</sup> mouse genotype at The Jackson Laboratories, and thus, it would be absent in C57. To control for contaminants in the PCR mixtures, a no DNA template control was analysed concurrently with regular DNA-containing samples. To ensure that the correct genotypes were visualised on gels a positive and negative control were included in all assays. The positive and negative controls contained DNA from known C57 and PAR<sub>2</sub><sup>-/-</sup>, respectively.

Standard agarose gel electrophoresis and DNA dye staining protocols were used to separate and then visualize the amplified DNA samples in order to identify the polymerase chain reaction products based on base pair lengths. Gels cast were (14 cm x 12 cm x 0.5 cm) 1.5 % agarose (w/v) Tris borate ethylenediaminetetraacetic acid (TBE) buffer containing Sybr® Safe DNA chelating dye. A loading dye (to allow experimenter to watch the progress of the electrophoretic separation) was added to polymerase chain reaction products. A DNA ladder of 100 base pair increments was used as a reference to identify the size of PCR products in parallel lanes. Gels were run for ~1.5 h at 90 V which produced clear separation of the DNA ladder base pairs and movement of the DNA primers > 4 cm from their wells. Polymerase chain reaction product DNA were imaged using Alpha Imager® EP, which used trans-ultraviolet light to illuminate DNA bands that

were stained by Sybr® safe.

### 3.6 Radiotelemetry

Physiological parameters were recorded in unrestrained mice using a radiotelemetry approach. Telemeters (TA11PA-C10, Data Sciences Inc.) were implanted following procedures described for recording blood pressure in aorta with access through the left carotid artery (McGuire et al., 2007). Telemeters were implanted into male mice 12-16 weeks of age, which weighed 22-34 g. Surgical procedures were 40-60 min and were followed by close observation for 48 h immediately after initial recovery from anesthesia. Recovery surgery was performed using a 3-stepped combination of isoflurane and oxygen anesthesia: induction: 100% O<sub>2</sub> (0.5 – 1 L/min) + isoflurane (3 - 4 %), maintenance: 100% O<sub>2</sub> (0.8 – 2 L/min) + isoflurane (1 – 2 %), and recovery: 100% O<sub>2</sub> (1 – 2 L/min). The final positions of the gel-filled catheter tip of the TA11PA-C10 telemeters, which were inserted into the left carotid artery and secured in position with silk ligatures, were verified later at necropsy. The TA11PA-C10 telemeter body was slid into a lateral subcutaneous pocket that had been filled with 0.2-0.5 ml saline. Saline (0.2 ml s.c.) and Duplocillin LA (0.02 ml intramuscular) were administered after all surgical wounds were closed with sutures. After wakening from anesthesia, mice were returned to their own cages and then transferred to a small animal intensive care unit, which provided a controlled temperature (30 °C) and humidity environment with a stream of oxygen (1 L/min) for 48 h post-operation observation.

Mice were allowed a 10 day recovery period before their baseline radiotelemetry

data were recorded. Five days (days -4 to -1) of continuous telemetry data were recorded as baseline using the proprietary DSI acquisition system, sampling the 3 s average for each variable every 30 s to produce 2880 data points for each variable per 24 h period. It is the standard practice of our laboratory that mice with 24 h mean pulse pressures less than 20 mmHg were excluded from subsequent data analysis because below this blood pressure the values may not be reliable (Van Vliet *et al.*, 2006).

### **3.7 Blood pressure and activity data analyses**

The variables measured by radiotelemetry in the unrestrained mice were mean (MAP), diastolic (DAP) and systolic arterial pressure (SAP), pulse pressure (PP), heart rate (HR) and locomotor activity. These data were exported into a Microsoft Excel worksheet-based template designed for routine analysis of telemetry data (HemoDynamic Statistics, 'HDstats' version 2006b-1.xls, July 2, 2006; Van Vliet *et al.*, 2006). This spreadsheet generates 500 statistics based on the recorded variables for each 24 h period. Data obtained on the day of pump implant (day 0) and cage change days (day 8 and 11) were excluded from analyses. Data points containing fewer than 3 mice were excluded from analyses. Baseline data were calculated from the total number of mice of each strain as shown in Table 8 (C57 n=6 and PAR<sub>2</sub><sup>-/-</sup> n=8). The statistical test to compare baseline data between strains was a Student's t-test for unpaired data. Two way ANOVA (pump x time) was used to compare the 24 h mean variables and changes of variables from baseline data.

The change from baseline data = values recorded on day x (where x is the day of pump implant) – mean of the baseline data.

Microsoft Excel and GraphPad Prizm software were used to manage data, perform statistical comparisons and create graphs.

### **3.8 Subcutaneous drug delivery**

Drug treatments were delivered by subcutaneous infusion using micro-osmotic pumps. Micro-osmotic pumps were filled with saline or peptide (2 $\mu$ l) then equilibrated 6-12 h at 37 °C as per manufacturer's instructions (Alzet). The micro-osmotic pumps were then implanted subcutaneously in anaesthetized mice through an incision on the dorsal neck into a small pocket filled with saline along the flank as described previously (McGuire *et al.*, 2008). Surgeries to implant micro-osmotic pumps lasted 5-10 min and were followed by 2 h of recuperation in the small animal intensive care unit for full apparent recovery. The anesthesia protocol was the same as for telemeter implants. Each mouse was also administered 0.2 ml of saline s.c. and 0.02 ml of Duplocillin LA (per ml, active portion contains 150,000 international units (IU) benzathine penicillin and 150,000 IU procaine penicillin, with methyl parahydroxybenzoate (1.2 mg) and propyl parahydroxybenzoate (0.13 mg) as preservatives) intramuscularly. After 2 h post-surgical recovery, the mice were returned to the room dedicated to radiotelemetry recordings in the animal care facility. Length of treatment (7, 14 days) and dose (low, LD and high, HD) of administered peptide were selected by choosing an appropriate micro-osmotic pump model and varying the concentration of drug in the pump reservoir (7 days: model

1007D, pump rate 0.5  $\mu\text{l/h}$ ; 14 day: model 1002, pump rate 0.25  $\mu\text{l/h}$ ). Concentrations of drug inside reservoirs were adjusted by dilution with bacteriostatic saline to match the dose delivery rate on the starting (pre-pump implant) weight basis for each mouse. Mice assigned to 2fly treatment received either HD (6 nmol/kg/min) or LD (2 nmol/kg/min). Since there were no literature references regarding chronic infusions with PAR<sub>2</sub>-AP at the initiation of these studies in September 2008 and because of practical considerations (amount of drug required and solubility), doses of 2fly were chosen based on a range of molar doses that were estimated to be in the equipotent molar dose range of SLIGRL-NH<sub>2</sub> used in acute studies of blood pressure effects (a 1 min i.v. infusion of 0.1, 0.3, 1  $\mu\text{mol}$  SLIGRL-NH<sub>2</sub> /kg in anaesthetized mice reduced MAP by 10-40 mmHg for up to 5 min (Cheung *et al.*, 1998)). We made an assumption that 2fly would be at least 100 - 300-times more potent than SLIGRL-NH<sub>2</sub> *in vivo* as it had been reported to be at least such *in vitro* (McGuire *et al.*, 2004a).

### **3.9 Isometric tension measurements of mouse aortas**

Mice were euthanized by overdose inhalation with isoflurane followed by a blood withdrawal by cardiac puncture using a syringe containing heparin (100 U). Thoracic descending aortas (1-2 cm) were removed and stored in ice-cooled Krebs's solution until cleaned of fat and adherent tissues. Two to four sections per aorta (2 mm lengths) were cut and mounted on 200  $\mu\text{m}$  diameter hooks in a 610 multi-myograph chamber (Danish Myograph Technologies, Aarhus, DK). Aortas were bathed in a physiological salt solution (pH 7.4) comprised of 114 mM NaCl, 4.7 mM KCl, 0.8 mM KH<sub>2</sub>PO<sub>4</sub>, 1.2 mM

MgCl<sub>2</sub>·6H<sub>2</sub>O, 2.5 mM CaCl<sub>2</sub>·2 H<sub>2</sub>O, 11 mM D-glucose, and 25 mM NaHCO<sub>3</sub>, while bubbled continuously with 95 % O<sub>2</sub>/ 5 % CO<sub>2</sub> at 37 °C. Tissues were equilibrated at resting tension for 30 min prior to addition of any drugs. A normalized resting tension was set similar to the methods adopted for small calibre arteries from mice (McGuire *et al.*, 2007), a procedure first developed by Mulvany and Halpern (1977) for rat small mesenteric arteries. A pilot study on mouse aortas indicated that in the hands of the author, an optimum acetylcholine-induced relaxation activity was achieved by a resting tension that was set to 90% of the internal circumference that was estimated to produce aorta wall stress equivalent to 7.98 kPa. Increasing concentrations of K<sup>+</sup> were added to test the viability and responsiveness of the tissues. Contraction data were obtained using either single doses (90 mM) or a cumulative series of doses (30 mM, 60 mM, 90 mM, and 120 mM). High K<sup>+</sup> concentration solutions were balanced for osmolality by removing equimolar amounts of Na<sup>+</sup>.

Tissue preparations that generated <4 mN/mm of force in response to exposure to any contractile agonist were excluded from analysis. Each myograph chamber contained 8 ml of solution so investigational compounds were diluted at least 1/100 (80 µl in 8 ml) by direct addition to the organ baths. Most compounds were dissolved in nanopure filtered distilled water except indomethacin and A23187, which were dissolved in 95 % ethanol/5% water and pure dimethyl sulfoxide, respectively.

Cumulative concentration-contraction response relationships were determined for phenylephrine (1 nM to 100 µM) and U46619 (1 nM to 1 µM). From these relationships

submaximal contractions (50-80%) were produced by addition of varying concentrations of U46619 (10 nM to 100 nM) rather than phenylephrine, which produced an average contraction <4 mN/mm of force. U46619-induced contractions were used to determine relaxation responses elicited by cumulative addition of various compounds. Such compounds included acetylcholine (1 nM to 100  $\mu$ M), nitroprusside (0.1 nM to 100  $\mu$ M), 2-furoyl-Leu-Ile-Gly-Arg-Leu-Orn-NH<sub>2</sub> (1 nM to 3  $\mu$ M), Thr-Phe-Leu-Leu-Arg-NH<sub>2</sub> (1 nM to 3  $\mu$ M), and A23187 (1 nM to 1  $\mu$ M). Inhibitors were incubated for 15 minutes prior to contraction. Inhibitors included L-NAME (300  $\mu$ M) and indomethacin (10  $\mu$ M).

Endothelium denudation of aortas was performed in order to investigate the endothelium-dependence of responses to specific drugs. Endothelial cells were damaged by rotating the aorta around the two hooks inside the myograph chambers. Resting (initial) tension was set by adjusting to the same length as prior to endothelium removal. Vessels were contracted by U46619 as before and acetylcholine, nitroprusside and 2fly (at concentrations above) were tested for endothelium dependence.

Continuous recording of isometric tension data were acquired via computer connections using MyoDaq/MyoData and ADI Instruments Chart 5 software packages. Data points representative of the maximal responses to each concentration of drug were selected and later exported to a master spreadsheet template file in Excel 2003.

### **3.10 Western Blots**

Protein was collected by homogenization of aortas in lysis buffer B (0.8 x TBS, pH 7.4) containing 10 % (v/v) glycerol, 1 % (v/v) NP-40, 1 mM NaF, 1 mM Na<sub>3</sub>VO<sub>4</sub>,

0.025 % (w/v) SDS and a standard protease inhibitor cocktail) with a glass micro tissue grinder (Wheaton) on ice. Samples were centrifuged at 14,000 rpm for 15 min in a microcentrifuge (Centrifuge 5415C, Eppendorf) and the supernatants were collected for protein concentration determination. Protein concentrations of supernatants were determined using Pierce bicinchoninic acid assay kit (Fisher; # 23227) with automated FluroStar microplate reader according to the manufacturer.

Individual proteins were separated by relative molecular weight using routine SDS PAGE (10% SDS; 8 % polyacrylamide crosslinking). Supernatant protein was added to lysis buffer B plus loading buffer containing dithiothreitol (DTT). A protein molecular weight ladder (Benchmark Prestained protein ladder, Invitrogen) was run in a parallel lane to allow determination of the relative molecular weights of immunoreactive bands. A positive control lane containing protein isolated from mouse vas deferens was used to validate the relative molecular weight of immunoreactive bands corresponding to cyclooxygenase-1 (COX-1) and cyclooxygenase-2 (COX-2). Although the specific antibodies for sGC and eNOS were already well characterized by others in a variety of vascular tissues, we confirmed the specificities with homogenized lung samples from mice in separate experiments. All samples including the positive controls, but not the ladder, were boiled at 100 °C for 5 min prior to loading on gels. Gels were run at 120 V until the dye front reached the end of the gel.

Proteins were transferred from the gel to polyvinylidene fluoride membranes by electrophoresis (1.5 h at 100 V) in ice cold transfer buffer comprised of 25 mM Tris-base

(pH 8.3), 192 mM glycine, and 10 % methanol. Membranes containing the proteins were washed with TBST buffer; TBS (pH 7.4) containing 0.1% Tween-20) then blocked (15 min) with a solution of TBST containing 3% (w/v) bovine serum albumin. Membranes were probed with antibodies for the proteins of interest as given in Appendix B; optimal conditions (dilutions) for each antibody had been determined in previous work of the laboratory. The blocked membranes and primary antibodies were incubated together overnight at 4 °C and then washed 4-times with TBST. Then an appropriate secondary antibody-linked to horseradish peroxidase was incubated together with membranes for 1 h at room temperature (~25 °C) before exposure to substrate and visualization of immunoreactive bands by enhanced chemiluminescence on photographic film. The developed films were scanned (Hewlett-Packard ScanJet 3300C) using Adobe Photoshop v8 software and then a file copy was converted to a JPEG format. These files were imported into ImageJ software for densitometric analyses of bands.

### **3.11 Immunohistochemistry**

Segments of saline and 2fly high dose-treated C57 and PAR<sub>2</sub><sup>-/-</sup> aortas were stored in optimal cutting temperature gel and sectioned using a cryotome at -20 °C. Frozen 8 μm sections (rings) were placed on gelatin-coated slides. These slides were stored at -20 °C until final use. They were probed by a primary antibody, SAM-11, a monoclonal antibody raised against human N-terminus of PAR<sub>2</sub> (Molino *et al.*, 1997), at different dilutions (1/50, 1/100, and 1/500) of a stock solution (0.2 mg/ml). A secondary antibody (anti-mouse IgG) labeled with FITC (dilution of 1/500; stock solution 1.5 mg/ml) was used to

detect the primary staining distribution. The FITC fluorescence emission was measured in response to 492 nm excitation light from an argon laser. The emitted FITC fluorescence was filtered at 520 nm (peak of emission spectrum of FITC) and imaged by a confocal microscope (Olympus Fluoview, FV300). Stack images from a 10  $\mu\text{m}$  depth of tissue sections were obtained by stepping up or down the confocal plan through the preparation (z step = 1  $\mu\text{m}$ ). Image analyses of 1  $\mu\text{m}$  sections were performed by randomly selecting three areas of each stack image. Image J (line tool) was used to quantify the fluorescence patterns across the length of the vessel wall. This was measured as pixel density per length of aortic wall at each 1 micron step, in the section. The patterns of pixel density were compared between other sections of the same sample type to determine a common representation if such existed. These were then compared between treatment and strains.

### 3.12 Statistical Analyses

Graph Pad Prizm v4 was used to create all graphs and conduct the statistical analyses. Unless otherwise stated, the drug concentration response curves (CRC) for each aorta were fit by nonlinear regression to a four parameter logistic equation with a fixed origin set to 0. Three parameters:  $\text{pD}_2$ ,  $E_{\text{max}}$ , and Hill slope, were used to determine changes in sensitivity, maximal effectiveness, and changes in relaxation curve kinetics, respectively. Hill slopes were not restricted to allow for differences in drug interactions.

The equation is as follows:

$$\% \text{ relaxation} = \text{Bottom} + (E_{\text{max}} - \text{Bottom}) / (1 + 10^{(\log \text{EC50} - \log [2\text{fly} (M)]) * \text{Hill slope}}); \text{bottom, constant} = 0; E_{\text{max}}, \text{maximum \% relaxation}; \text{pD}_2, \text{negative}$$

logarithm base 10 of EC50 value.

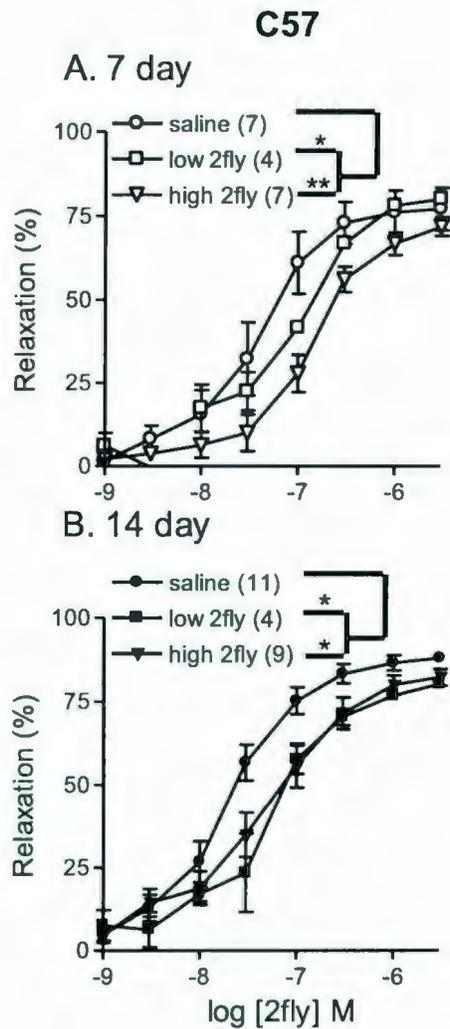
Data that were not good fits ( $R^2 < 0.8$ ) by the nonlinear regression method, e.g. some inhibitor treatments and A23187 responses, were analyzed using alternative or additional approaches as described in the appropriate section of results. Statistical comparison of the means of more than two independent groups were made by two way ANOVA (main effects were pump and time) and were followed by a Bonferroni post-hoc test. Statistical analysis of three groups with one independent variable was made by one way ANOVA. Statistical comparisons that involved the means of only two groups were made by Student's t-test for unpaired data.  $P < 0.05$  was considered significant. (n) represents the number of independent samples i.e. n equals the number of mice per group. Error bars on graphs represent the standard error of mean.

## **Chapter 4: Results**

### **4.1 Effect of chronic PAR<sub>2</sub> activation on NO-mediated relaxation of aortas**

#### **4.1.1 2fly Relaxation**

We measured 2fly relaxation after chronic PAR<sub>2</sub>-AP treatment and saline treatment to determine if these treatments affected PAR<sub>2</sub> reactivity in aortas. Chronic PAR<sub>2</sub>-AP caused a 3- (LD) to 4-fold (HD) decrease in sensitivity for 2fly CRC in C57 aortas represented by decreased pD<sub>2</sub> values (Table 4.1) and a rightward shift in the curve (Figure 4.1A) at 7 days. At 14 days a 3-fold (LD) and a 2-fold (HD) difference was observed in pD<sub>2</sub> values as well as a rightward shift in the CRC (Figure 4.1B). The E<sub>max</sub>



**Figure 4.1. Effect of PAR<sub>2</sub>-AP s.c. infusions for 7 (A) and 14 (B) days on 2fly-induced relaxations of isolated C57 aortas.** Mice were implanted with 7 (A) and 14 (B) day pumps s.c. Isolated aortas were contracted submaximally (50-80%) by U46619 prior to determining relaxation by 2fly. Values in parentheses are the number of mice. \* P<0.05 for pD<sub>2</sub>, saline vs. low 2fly 7 days, saline vs. low and high 2fly 14 days and \*\* P<0.01 for pD<sub>2</sub>, saline vs. high 2fly 7days 2way ANOVA, Bonferroni.

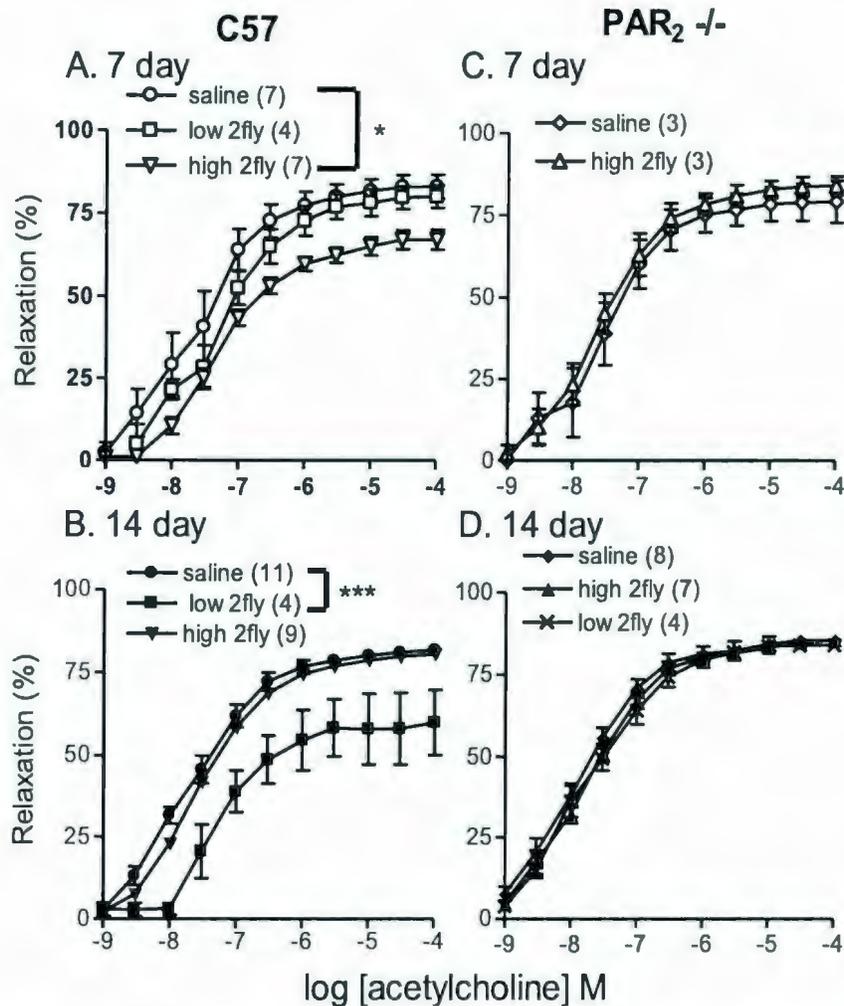
and hill slopes for 2fly CRC were not different between groups (Table 4.1). Aortas of  $PAR_2^{-/-}$  mice showed no relaxation or contraction to cumulative addition of 2fly. These data indicate the decrease in  $PAR_2$ -AP sensitivity in C57 was dependent on *in vivo* dose and length of infusions.

2fly		micro-Osmotic Pump Treatment											
Duration (days)	Artery Treatment	n	Saline			2fly low dose				2fly high dose			
			pD <sub>2</sub> (M)	E <sub>max</sub> (%)	Hill Slope	n	pD <sub>2</sub> (M) <sup>a,b</sup>	E <sub>max</sub> (%)	Hill Slope	n	pD <sub>2</sub> (M) <sup>a,b</sup>	E <sub>max</sub> (%)	Hill Slope
7	Control	7	7.5(0.1)	82(2)	3.1(1.6)	4	7.0(0.1) <sup>c</sup>	75(5)	0.8(0.1)	7	6.9(0.1) <sup>d</sup>	77(3)	1.6(0.2)
	L-NAME	5	n/d	16(7)	n/d	4	n/d	18(4)	n/d	4	n/d	10(5)	n/d
	indomethacin	6	7.3(0.2)	74(7)	4.6(2.2)	-	-	-	-	7	6.8(0.1)	67(3)	4.7(4.1)
14	Control	11	7.7(0.1)	86(2)	1.4(0.2)	4	7.3(0.1) <sup>c</sup>	80(1)	1.0(0.3)	9	7.4(0.1) <sup>c</sup>	82(3)	0.9(0.1)
	L-NAME	7	n/d	13(6)	n/d	4	n/d	7(5)	n/d	4	n/d	25(12)	n/d
	indomethacin	11	7.4(0.1)	76(3)	3.9(1.3)	-	-	-	-	9	6.7(0.3) <sup>c</sup>	84(18)	4.8(1.6)

**Table 4.1. Parameters for 2fly CRC in saline and 2fly treated C57 mice in the presence of nonselective inhibitors of NOS and COX.** Values are mean (SE), n = mice/ group. Variables were determined by nonlinear regression curve fitting of the averaged 2fly concentration-relaxation responses for each mouse using a four parameter logistic equation. n/d indicates data that could not be fit to equation. -, not tested. 2fly low dose, 2 nmol/kg/min, 2fly high dose, 6 nmol/kg/min; L-NAME, 300 μM; indomethacin, 10 μM. Statistics tests (2 way ANOVA) indicating significant main effects and interactions were followed by Bonferroni post-hoc testing for multiple comparison testing. <sup>a</sup> P<0.001, significant effect of pump. <sup>b</sup> P<0.01, significant effect of time. <sup>c</sup> P<0.05, compared to saline in each group (Bonferroni). <sup>d</sup> P<0.01, compared to saline in each group (Bonferroni). <sup>e</sup> P<0.001, compared to control with the same treatment (Bonferroni).

#### 4.1.2 Acetylcholine Relaxation

Acetylcholine-induced relaxations were measured to determine if there was a change in endothelium-dependent nitric oxide relaxations by PAR<sub>2</sub>-AP *in vivo* treatments. Acetylcholine E<sub>max</sub> values in C57 aortas were attenuated by 16% and 25% after 7 days of HD and 14 days of LD PAR<sub>2</sub>-AP treatment, respectively, compared to controls (Table 4.2, Figure 4.2A and B). pD<sub>2</sub> and hill slope values for ACh CRC were not different across all groups. ACh CRC of aortas from chronic PAR<sub>2</sub>-AP treated PAR<sub>2</sub><sup>-/-</sup> were not different than in saline-treated PAR<sub>2</sub>-AP (Figure 4.2C and D, Table 4.3). These data indicate endothelium-dependent nitric oxide relaxation was reduced by specific doses and duration of exposure to PAR<sub>2</sub>-AP in C57 mice.



**Figure 4.2. Effect of PAR<sub>2</sub>-AP s.c. infusions for 7 (A, C) and 14 (B, D) days on acetylcholine-induced relaxations of isolated C57 aortas PAR<sub>2</sub><sup>-/-</sup> aortas.** Mice were implanted with 7 (A, C) and 14 (B, D) day pumps s.c. Isolated aortas were contracted submaximally (50-80%) by U46619 prior to determining relaxation by acetylcholine. Values in parentheses are the number of mice. \* P<0.05 E<sub>max</sub>, 7 day saline vs. 7 day 2fly high dose and \*\*\* P<0.001 E<sub>max</sub>, 14 day saline vs. 14 day 2fly low dose by 2 way ANOVA, Bonferroni.

acetylcholine			micro-Osmotic Pump Treatment										
Duration (days)	Artery Treatment	n	Saline			2fly low dose				2fly high dose			
			pD <sub>2</sub> (M)	E <sub>max</sub> (%)	Hill Slope	n	pD <sub>2</sub> (M)	E <sub>max</sub> <sup>a,b</sup> (%)	Hill Slope	n	pD <sub>2</sub> (M)	E <sub>max</sub> <sup>a,b</sup> (%)	Hill Slope
7	Control	7	7.6(0.2)	81(3)	1.2(0.2)	4	7.3(0.1)	76(3)	0.9(0.1)	7	7.2(0.1)	68(3) <sup>c</sup>	0.9(0.1)
	L-NAME	5	n/d	23(12)	n/d	4	n/d	28(8)	n/d	4	n/d	23(15)	n/d
	Indomethacin	6	7.3(0.1)	69(9)	1.5(0.3)	-	-	-	-	7	6.9(0.2)	66(8)	1.2(0.3)
14	Control	11	7.6(0.1)	81(2)	0.9(0.1)	4	7.2(0.1)	61(9) <sup>d</sup>	1.1(0.2)	9	7.5(0.1)	81(3)	0.9(0.1)
	L-NAME	7	n/d	24(12)	n/d	4	n/d	23(10)	n/d	4	n/d	27(12)	n/d
	Indomethacin	11	7.7(0.4)	72(5)	4.2(2.4)	-	-	-	-	9	7.3(0.2)	78(3)	1.5(0.4)

**Table 4.2. Parameters for acetylcholine CRC in saline and 2fly treated C57 mice in the presence of nonselective**

**inhibitors of NOS and COX.** Values are mean (SE), n = mice/ group. Variables were determined by nonlinear regression curve fitting of the averaged acetylcholine concentration-relaxation responses for each mouse using a four parameter logistic equation. n/d indicates data that could not be fit to equation. -, not tested. 2fly low dose, 2 nmol/kg/min; 2fly high dose, 6 nmol/kg/min; L-NAME, 300 μM; indomethacin, 10 μM. Statistics tests (2 way ANOVA) indicating significant main effects and interactions were followed by Bonferroni post-hoc testing for multiple comparison testing. <sup>a</sup> P<0.005, significant interaction between pump and time. <sup>b</sup> P<0.01, significant effect of time. <sup>c</sup> P<0.05, compared to saline in same group.

<sup>d</sup> P<0.001, compared to saline in same group.

acetylcholine			micro-Osmotic Pump Treatment										
Duration (days)	Artery Treatment	n	Saline			2fly low dose				2fly high dose			
			pD <sub>2</sub> (M)	E <sub>max</sub> (%)	Hill Slope	n	pD <sub>2</sub> (M)	E <sub>max</sub> (%)	Hill Slope	n	pD <sub>2</sub> (M)	E <sub>max</sub> (%)	Hill Slope
7	Control	3	7.5(0.2)	78(6)	1.0(0.2)	-	-	-	-	3	7.6(0.1)	83(3)	1.0(0.1)
	Indomethacin	3	7.2(0.1)	75(1)	1.8(0.2)	-	-	-	-	3	7.6(0.1)	65(20)	3.7(2.7)
14	Control	8	7.9(0.1)	85(2)	0.9(0.1)	4	7.7(0.1)	84(1)	0.81(0.06)	7	7.7(0.1)	84(2)	0.9(0.1)
	Indomethacin	7	7.4(0.3)	68(7)	4.4(2.1)	-	-	-	-	7	7.8(0.3)	76(7)	2.9(1.9)

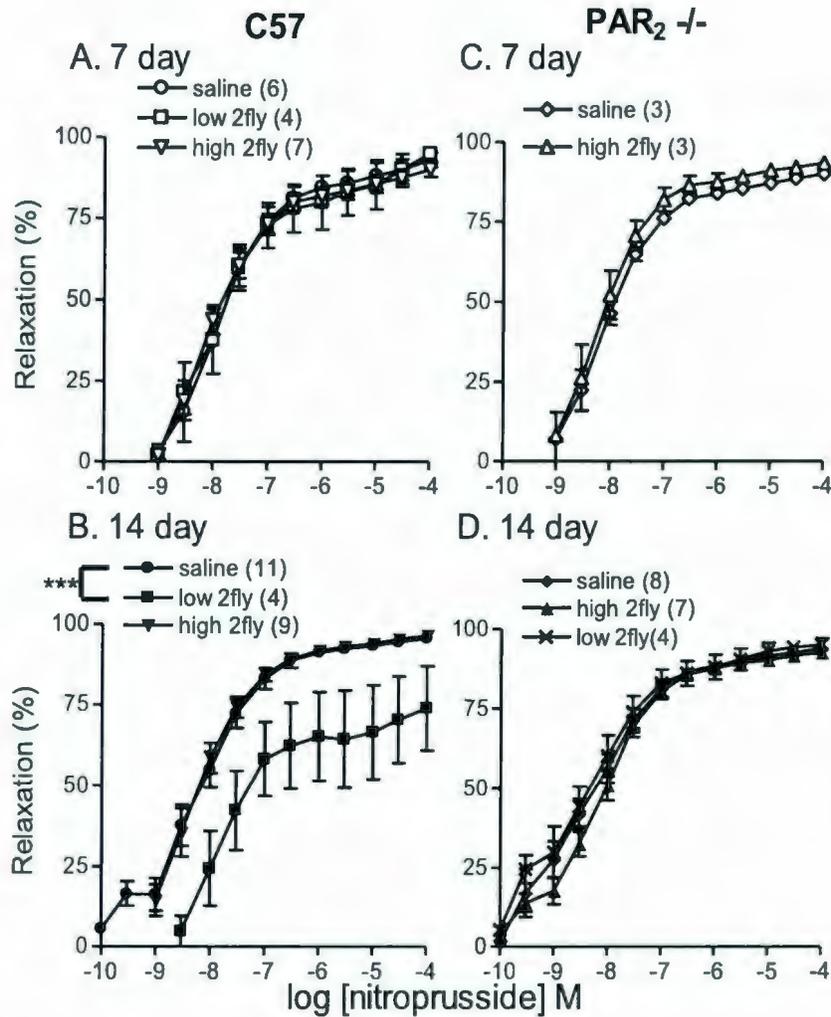
**Table 4.3. Parameters for acetylcholine CRC in saline and 2fly treated PAR<sub>2</sub><sup>-/-</sup> mice in the presence of nonselective inhibitors of NOS and COX.** Values are mean (SE), n = mice/ group. Variables were determined by nonlinear regression curve fitting of the averaged acetylcholine concentration-relaxation responses for each mouse using a four parameter logistic equation. -, not tested. 2fly low dose, 2 nmol/kg/min; 2fly high dose, 6 nmol/kg/min; indomethacin, 10 μM. Statistics tests (2 way ANOVA) indicating significant main effects and interactions were followed by Bonferroni post-hoc testing for multiple comparison testing. No significant differences were found.

#### 4.1.3 Nitroprusside Relaxation

Nitroprusside relaxations were measured to determine if there was a change in endothelium-independent nitric oxide-mediated relaxation by PAR<sub>2</sub>-AP treatments. PAR<sub>2</sub>-AP treatment *in vivo* caused time and dose dependent effects on nitroprusside CRC of mouse aortas. After 14 days LD PAR<sub>2</sub>-AP treatment, nitroprusside E<sub>max</sub> was attenuated by ~28% compared to C57 controls (Figure 4.3B, Table 4.4). Nitroprusside E<sub>max</sub> values were not significantly different between HD PAR<sub>2</sub>-AP and saline treatments (Table 4.4). pD<sub>2</sub> and hill slopes of nitroprusside CRC were not different among groups (Table 4.4). Nitroprusside CRC in PAR<sub>2</sub><sup>-/-</sup> were not affected by chronic PAR<sub>2</sub>-AP treatment (Figure 4.3C and D, Table 4.5). These data indicate that at 14 day LD PAR<sub>2</sub>-AP treatment there was an unexpected decrease in endothelium-independent nitric oxide-mediated relaxation.

#### 4.1.4 A23187 Relaxation

A23187 relaxations were measured to determine if there was a change in receptor-independent endothelium-dependent nitric oxide relaxations by PAR<sub>2</sub>-AP treatments. Relaxations mediated by A23187 were not found to differ between any of the groups (Figure 4.4; compare 1 μM responses for saline versus 2fly-treated, Student's t-test, P>0.05). We noted that tissue responses observed at 3 μM A23187 were highly variable. The solubility of 3 μM A23187 was poor, and thus, the relaxation data obtained at the highest concentrations may not be reliable. No differences in receptor-independent endothelium-dependent nitric oxide relaxation were found.



**Figure 4.3. Effect of PAR<sub>2</sub>-AP s.c. infusions for 7 (A, C) and 14 (B, D) days on nitroprusside-induced relaxations of isolated C57 and PAR<sub>2</sub><sup>-/-</sup> aortas.** Mice were implanted with 7 (A, C) and 14 (B, D) day pumps s.c. Isolated aortas were contracted submaximally (50-80%) by U46619 prior to determining relaxation by nitroprusside. Values in parentheses are the number of mice. \*\*\* P<0.001 E<sub>max</sub>, 14 day saline vs. 14 day low dose 2fly, by 2 way ANOVA, Bonferroni.

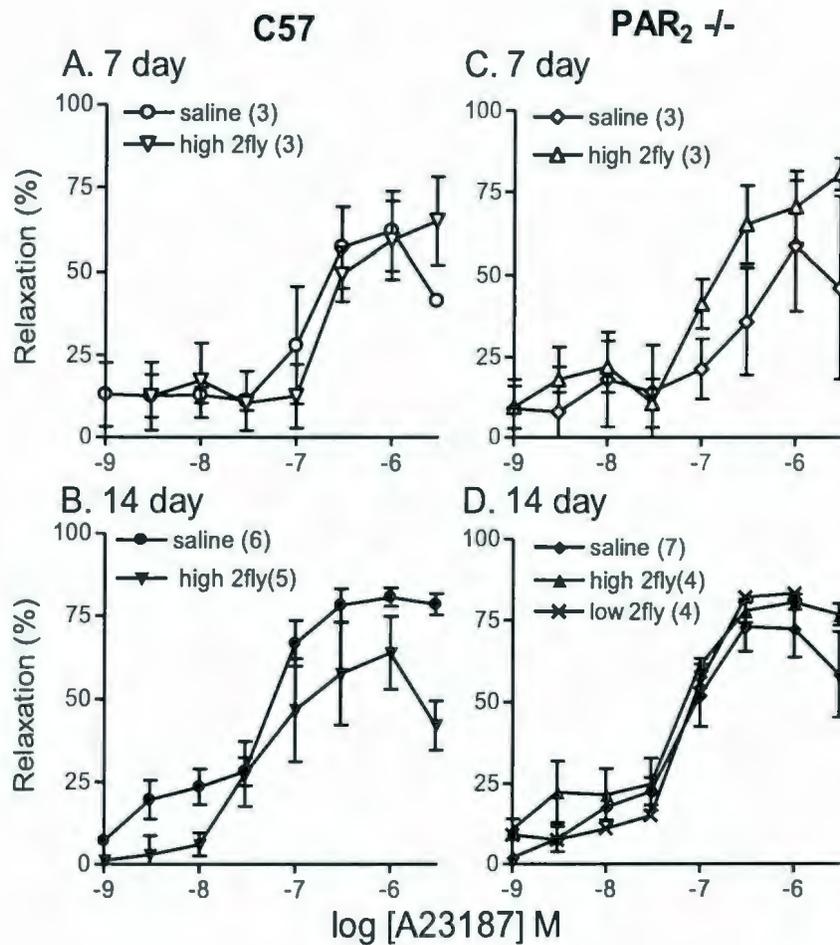
nitroprusside			micro-Osmotic Pump Treatment										
Duration (days)	Artery Treatment	n	Saline			2fly low dose				2fly high dose			
			pD <sub>2</sub> (M)	E <sub>max</sub> (%)	Hill Slope	n	pD <sub>2</sub> (M)	E <sub>max</sub> <sup>a,b</sup> (%)	Hill Slope	n	pD <sub>2</sub> (M)	E <sub>max</sub> <sup>a,b</sup> (%)	Hill Slope
7	Control	6	7.8(0.2)	93(2)	0.9(0.1)	4	7.8(0.2)	87(6)	0.9(0.1)	7	7.8(0.1)	90(2)	0.9(0.1)
	L-NAME	5	8.1(0.2)	92(4)	1.1(0.2)	4	8.3(0.1)	94(2)	0.9(0.1)	4	7.9(0.1)	91(3)	0.8(0.1)
	Indomethacin	6	7.6(0.8)	90(3)	0.9(0.2)	-	-	-	-	7	8.4(0.1)	83(7)	2.5(1.7)
14	Control	11	8.2(0.1)	93(1)	1.0(0.1)	4	7.7(0.1)	67(14) <sup>c</sup>	1.5(0.3)	9	8.2(0.1)	96(1)	0.8(0.1)
	L-NAME	7	7.9(0.2)	91(2)	1.0(0.1)	4	8.2(0.2)	92(1)	1.0(0.1)	4	7.0(0.2)	93(1)	1.1(0.2)
	Indomethacin	11	8.0(0.2)	84(4)	2.7(1.0)	-	-	-	-	7	8.4(0.1)	91(1)	1.6(0.5)

**Table 4.4. Parameters for nitroprusside CRC in saline and 2fly treated C57 mice in the presence of nonselective**

**inhibitors of NOS and COX.** Values are mean (SE), n = mice/ group. Variables were determined by nonlinear regression curve fitting of the averaged nitroprusside concentration-relaxation responses for each mouse using a four parameter logistic equation. n/d indicates data that could not be fit to equation. -, not tested. 2fly low dose, 2 nmol/kg/min; 2fly high dose, 6 nmol/kg/min; L-NAME, 300 μM; indomethacin, 10 μM. Statistics tests (2 way ANOVA) indicating significant main effects and interactions were followed by Bonferroni post-hoc testing for multiple comparison testing.<sup>a</sup> P<0.05, significant interaction between pump and time. <sup>b</sup> P<0.001, significant effect of pump. <sup>c</sup> P<0.001, compared to saline in same group (Bonferroni).

nitroprusside			micro-Osmotic Pump Treatment										
Duration (days)	Artery Treatment	n	Saline			2fly low dose				2fly high dose			
			pD <sub>2</sub>	E <sub>max</sub> (%)	Hill Slope	n	pD <sub>2</sub>	E <sub>max</sub> (%)	Hill Slope	n	pD <sub>2</sub>	E <sub>max</sub> (%)	Hill Slope
7	Control	3	8.0(0.1)	87(1)	1.0(0.18)	-	-	-	-	3	8.1(0.2)	90(1)	1.0(0.1)
	Indomethacin	3	7.9(0.2)	89(7)	0.6(0.2)	-	-	-	-	3	7.3(0.9)	92(4)	3.4(2.1)
14	Control	8	8.4(0.1)	92(1)	0.7(0.1)	4	8.5(0.2)	94(2)	0.6(0.1)	7	8.2(0.1)	91(1)	0.8(0.1)
	Indomethacin	7	8.1(0.1)	85(2)	1.0(0.3)	-	-	-	-	7	8.1(0.2)	82(3)	0.9(0.1)

**Table 4.5. Parameters for nitroprusside CRC in saline and 2fly treated PAR<sub>2</sub><sup>-/-</sup> mice in the presence of nonselective inhibitors of NOS and COX.** Values are mean (SE), n = mice/ group. Variables were determined by nonlinear regression curve fitting of the averaged nitroprusside concentration-relaxation responses for each mouse using a four parameter logistic equation. n/d indicates data that could not be fit to equation. -, not tested. 2fly low dose, 2 nmol/kg/min; 2fly high dose, 6 nmol/kg/min; indomethacin, 10 μM. Statistics tests (2 way ANOVA) indicating significant main effects and interactions were followed by Bonferroni post-hoc testing for multiple comparison testing. No significant differences were found.



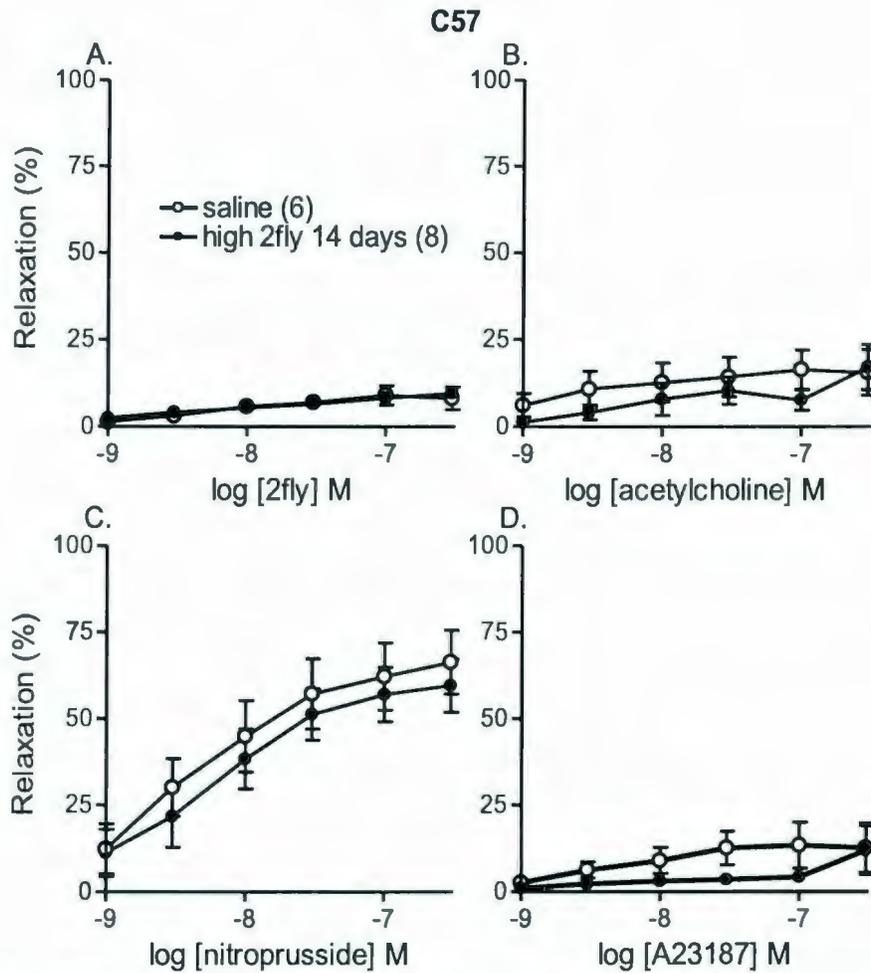
**Figure 4.4.** Effect of PAR<sub>2</sub>-AP s.c. infusions for 7 (A, C) and 14 (B, D) days on A23187-induced relaxations of isolated C57 and PAR<sub>2</sub><sup>-/-</sup> aortas. Mice were implanted with 7 (A, C) and 14 (B, D) day pumps s.c. Isolated aortas were contracted submaximally (50-80%) by U46619 prior to determining relaxation by A23187. Values in parentheses are the number of mice. The maximal relaxations did not differ amongst groups A, B, and C (Students t-test) and D (one way ANOVA).

#### **4.1.5 Intact versus denuded endothelium**

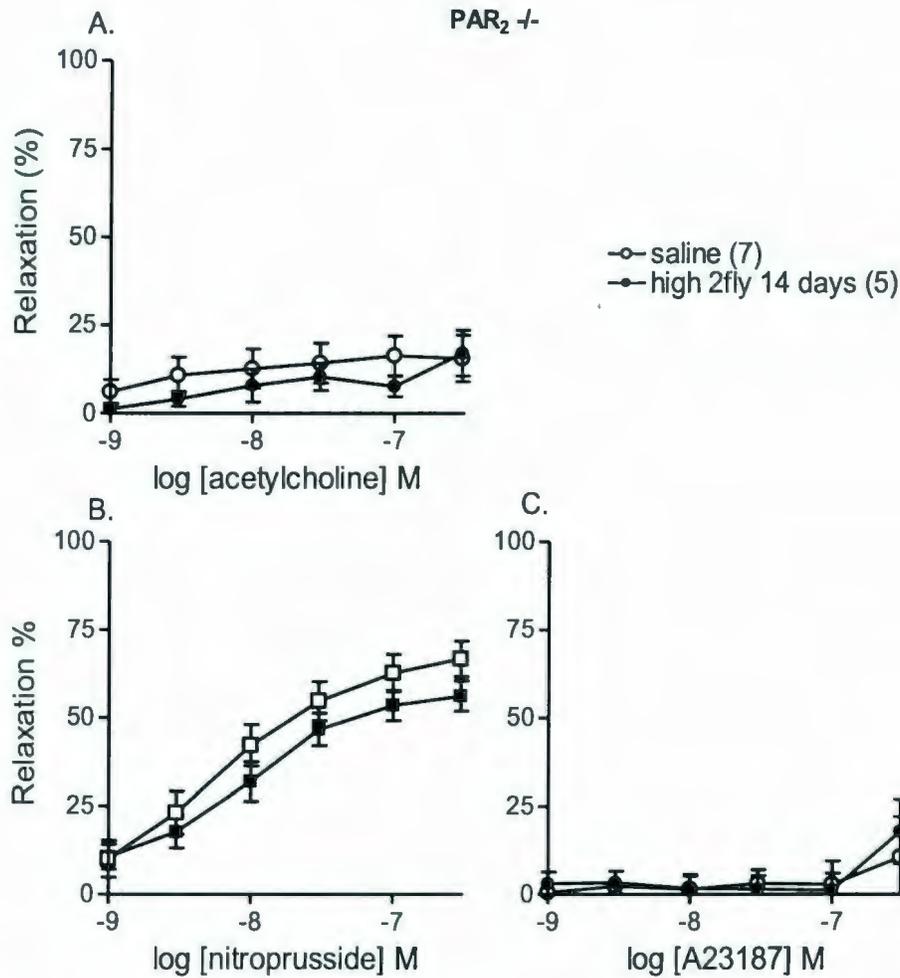
To describe the agonists' dependencies on intact endothelium, aortas were subjected to endothelial cell denudation by rotating the aortas on wires in the myograph chambers. ACh, 2fly, and A23187 were found to be all endothelium-dependent as they caused minor if any relaxation in the denuded aortas of C57 or PAR<sub>2</sub><sup>-/-</sup> (Figures 4.5 and 4.6). Nitroprusside did elicit relaxation of denuded aorta, albeit reduced, in both C57 and PAR<sub>2</sub><sup>-/-</sup>, indicating relaxation was independent of endothelium (Figures 4.5 and 4.6). The agonists showed specificity to endothelium as expected.

#### **4.1.6 Effect of eNOS and COX inhibition on vasodilators**

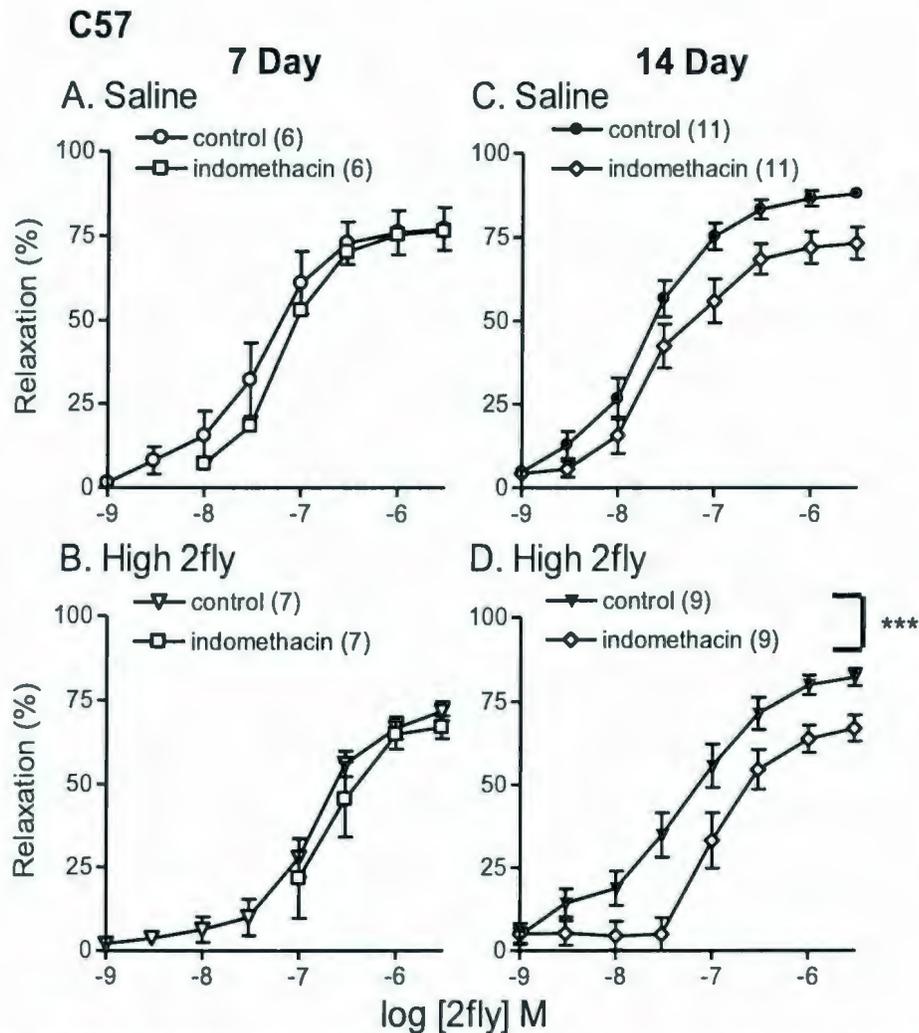
To determine underlying mechanisms of NO-dependent drugs the effect of inhibition of eNOS and cyclooxygenases were measured using L-NAME and indomethacin respectively. L-NAME dramatically inhibited relaxation by 2fly (Table 4.1) and acetylcholine (Table 4.2) but had no effect on nitroprusside CRC (Table 4.4) in either treatment group. E<sub>max</sub> values for 2fly and acetylcholine (Tables 4.1 and 4.2) CRC in the presence of L-NAME were significantly reduced compared to controls (P<0.001, 2 way ANOVA). E<sub>max</sub>, pD<sub>2</sub>, and hill slope of nitroprusside CRC in the presence of L-NAME (Tables 4.4) were not different than untreated aortas (P>0.05, 2 way ANOVA). Indomethacin pretreatment of aortas caused a rightward shift as measured by a reduction in pD<sub>2</sub> values for 2fly relaxation in C57 2fly HD 14 day treated mice as illustrated in Figure 4.7D and Table 4.1 (P<0.001). In summary, inhibition of eNOS caused expected reductions in relaxation while blocking cyclooxygenases caused a rightward shift.



**Figure 4.5. Effect of endothelium denudation of C57 aortas on 2fly-, acetylcholine-, nitroprusside- and A23187-induced relaxations.** The endothelium was removed from aortas by rotating them around hooks prior to setting ring tension. Aortas were then contracted by U46619 and then exposed to 2fly, acetylcholine, nitroprusside and A23187. Values in parentheses are the number of mice. All data points for 2fly, ACh, and A23187 (A, B, D), but not nitroprusside (C) were not different than zero (one sample Students t-test). In C, saline vs. 2fly, the maximal response was not significantly different (Students t-test).



**Figure 4.6. Effect of endothelium denudation of PAR<sub>2</sub><sup>-/-</sup> aortas on acetylcholine-, nitroprusside- and A23187-induced relaxations.** The endothelium was removed from aortas by rotating them around hooks prior to setting resting tension. Aortas were contracted by U46619 and then exposed to acetylcholine, nitroprusside, and A23187. Values in parentheses are the number of mice. All data points for ACh and A23187 (A and C), but not nitroprusside (B) were not different than zero (one sample Students t-test). In B, saline vs. 2fly, the maximal response was not significantly different (Students t-test).



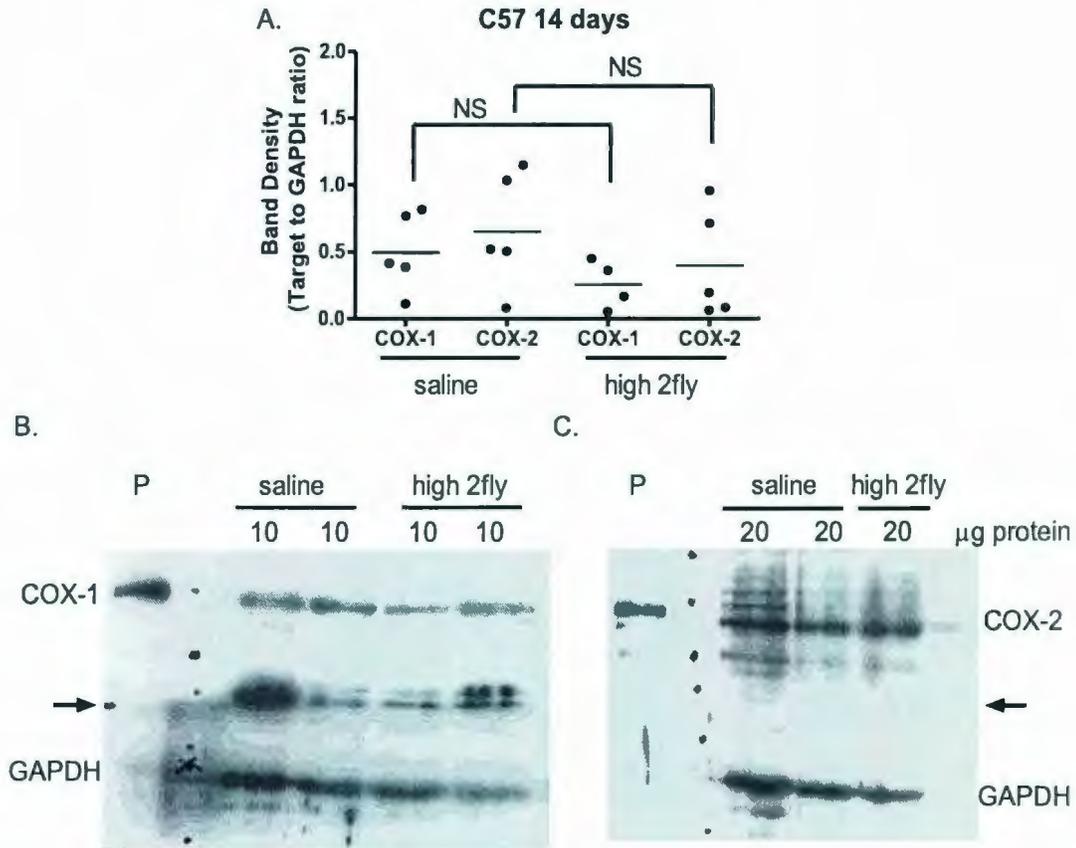
**Figure 4.7. Effect of indomethacin on 2fly-induced relaxations of aortas from PAR<sub>2</sub>-AP treated C57.** Mice were treated with saline (A, C) or high dose 2fly (B, D) s.c. for 7 (A, B) or 14 (C, D) days. Isolated aortas were pretreated with indomethacin (10  $\mu$ M) for 15 min prior to submaximal contraction by U46619 (50-80 %) and then exposing to 2fly. Values in parentheses are the number of mice. \*\*\*  $P < 0.001$  pD<sub>2</sub>, 14 day 2fly control vs. 14 day 2fly indomethacin, by 2 way ANOVA, Bonferroni.

#### **4.2 Chronic PAR<sub>2</sub>-AP treatment effect on expressions of COX isoforms 1 and 2, eNOS and sGC in mouse aortas**

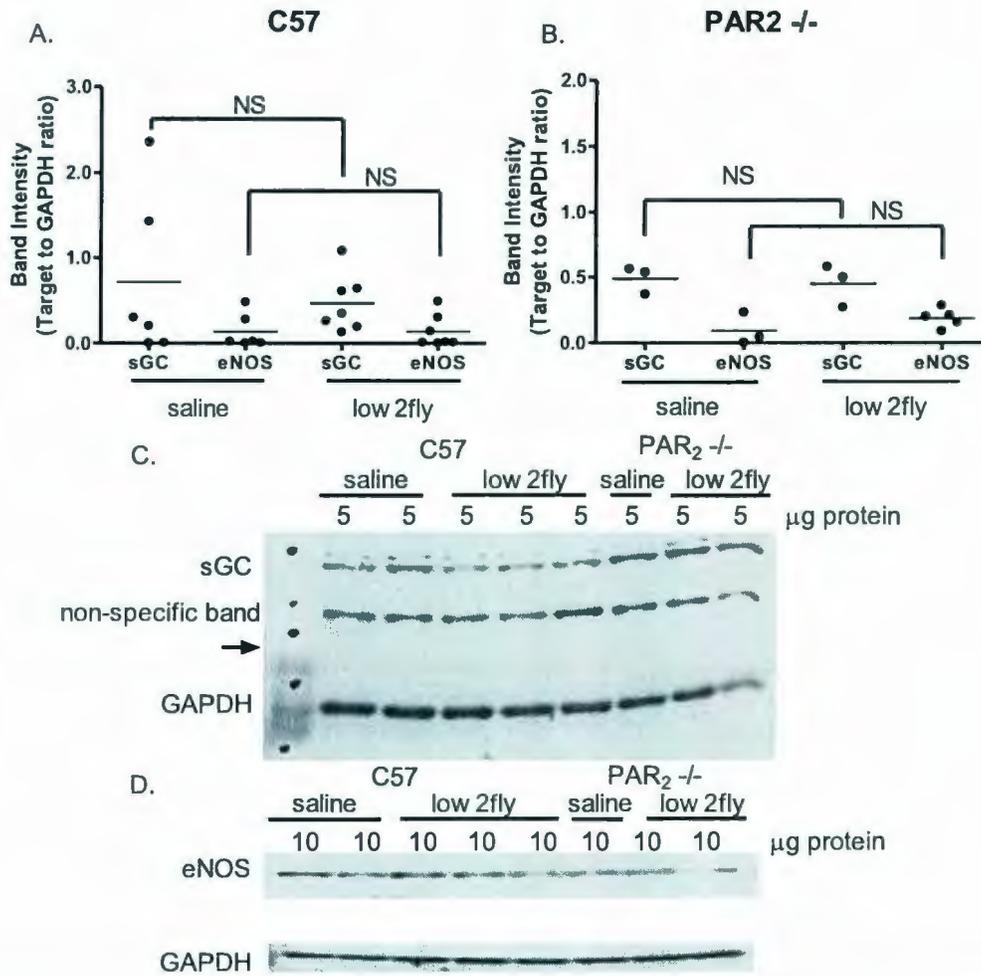
Measurement of COX isoforms, eNOS, and sGC in aortic rings was performed to identify if the changes in aortic functional responses were due in part to changes in protein expression of components involved in the relaxation mechanism.

Immunoreactivity indicative of COX-1, COX-2, eNOS and sGC were detected in aortic protein from both saline and PAR<sub>2</sub>-AP treated animals (Figure 4.8B, and 4.9C).

Densitometric analyses of target bands indicated the relative expression of COX-1 and COX-2 did not differ between saline-treated and PAR<sub>2</sub>-AP treated C57 aortas (Figure 4.8A). Expression of sGC and eNOS were not significantly different between saline and PAR<sub>2</sub>-AP treatments (Figure 4.9A) as well as between strains (Figure 4.9B). These data indicate the change seen in aortic responsiveness did not have a corresponding change in these target proteins between groups.



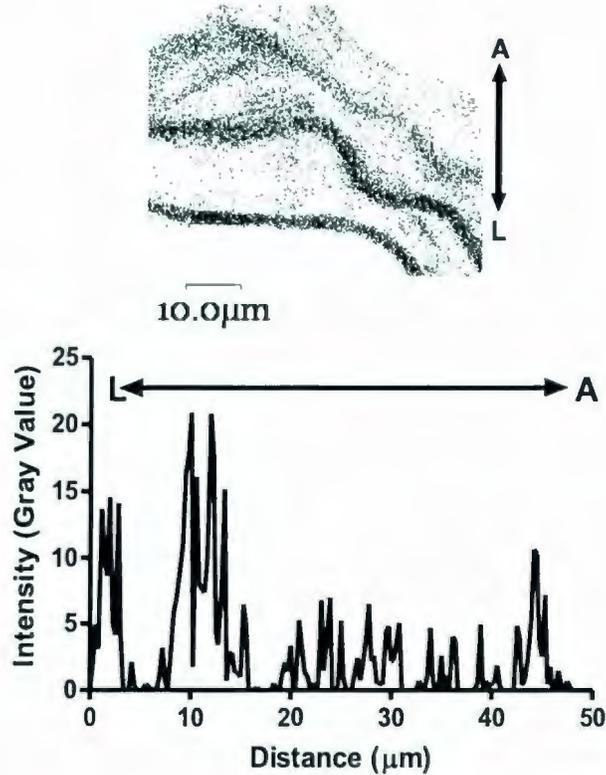
**Figure 4.8. Expression of COX-1 and COX-2 proteins in aortas of C57 mice infused s.c. with saline or high dose 2fly for 14 days. (A) Summary of densitometry of COX-1 and COX-2 in C57 mice compared to GAPDH from saline and high dose 2fly treated animals. Each symbol indicates an independent sample. Representative western blots for COX-1 (B) and COX-2 (C). P, indicates positive control sample (0.5 µg vas deferens protein). Arrows represent where the membranes were cut to immunoblot for GAPDH.  $P > 0.05$ , saline vs. high 2fly, Student's t-test.**



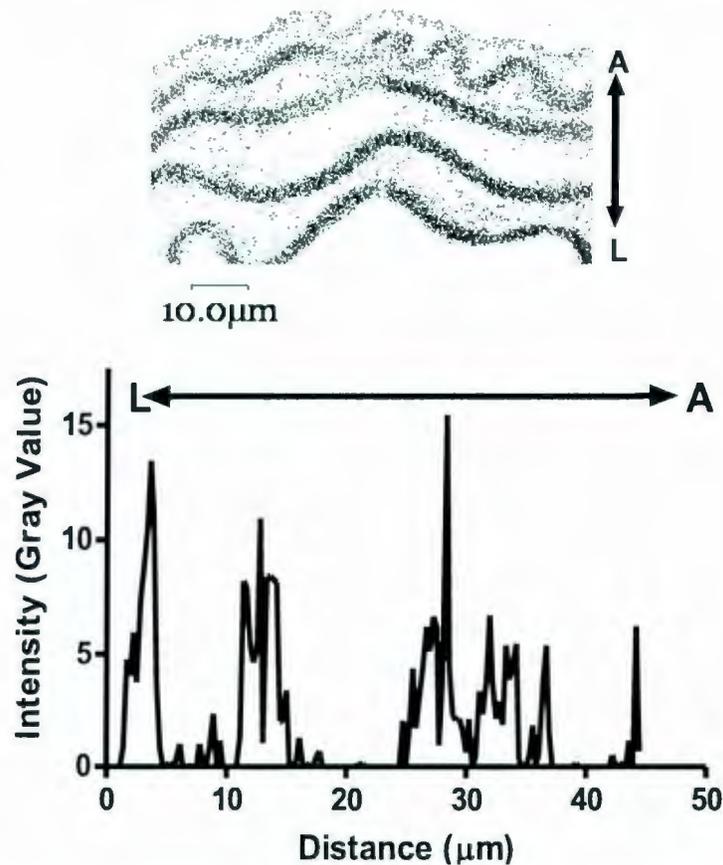
**Figure 4.9. Expression of sGC and eNOS protein in aortas of C57 and PAR<sub>2</sub><sup>-/-</sup> mice infused s.c. with saline or low dose 2fly for 14 days. Summary of densitometry of sGC and eNOS in C57 (A) and PAR<sub>2</sub><sup>-/-</sup> (B) mice compared to GAPDH from saline and low dose 2fly treated animals. Each symbol indicates an independent sample. Representative western blots for sGC (C) and eNOS (D). Arrows represent where the membranes were cut. P>0.05, saline vs. low 2fly, Student's t-test.**

### **4.3 Characteristics of SAM11 “anti-PAR<sub>2</sub>” antibody immunofluorescence in mouse aortas**

PAR<sub>2</sub> immunofluorescence experiments were performed to determine if the changes in aortic function to 2fly was due to a change in the amount of receptor present in the vessel wall. SAM11 antibody staining of aortas from both C57 and PAR<sub>2</sub><sup>-/-</sup> was detected by immunofluorescence using confocal microscopy (Upper panels of Figures 4.10 and 4.11). Qualitatively the images did not differ (Upper panels of Figures 4.10 and 4.11). Quantifying the pixel density distribution across the aortic wall (from lumen to exterior) indicated no obvious differences in the fluorescence signal pattern for either strain or treatment groups (Bottom panels of Figure 4.10 and 4.11). From the immunostaining procedure used we were unable to measure any differences in PAR<sub>2</sub> tissue distribution.



**Figure 4.10. Immunofluorescence of SAM11 antibody staining in C57 aortas.** Image (upper panel; 1 μm confocal plane steps) from frozen section of aorta (8 micron thick) incubated with primary antibody SAM11 (anti-PAR<sub>2</sub>) followed by secondary antibody FITC. Shown above is C57 2fly treated HD, SAM11, dilution 1:100 and FITC, dilution 1:100. Lower panel is a representative line scan of pixel intensity across the aortic wall using ImageJ software. The acquired colour confocal image was modified for reproduction purposes only and shown as above. Using Adobe Professional software the acquired image was grayscaled, inverted and the contrast was increased. In the original image black (empty) background and green immunofluorescence are reproduced as white and black, respectively. L, lumen and A, adventitia.



**Figure 4.11. Immunofluorescence of SAM11 antibody staining in  $PAR_2^{-/-}$  aortas.**

Image (upper panel; 1  $\mu$ m confocal plane steps) from frozen section of aorta (8 micron thick) incubated with primary antibody SAM11 (anti- $PAR_2$ ) followed by secondary antibody FITC. Shown above is  $PAR_2^{-/-}$  control, SAM11, dilution 1:100 and FITC, dilution 1:100. Lower panel is a representative line scan of pixel intensity across the aortic wall using ImageJ software. Using Adobe Professional software the acquired color confocal image was grayscale, inverted and the contrast was increased. In the original image black (empty) background and green immunofluorescence are reproduced as white and black, respectively. L, lumen and A, adventitia.

#### 4.4 Blood pressure, heart rate and locomotor activity

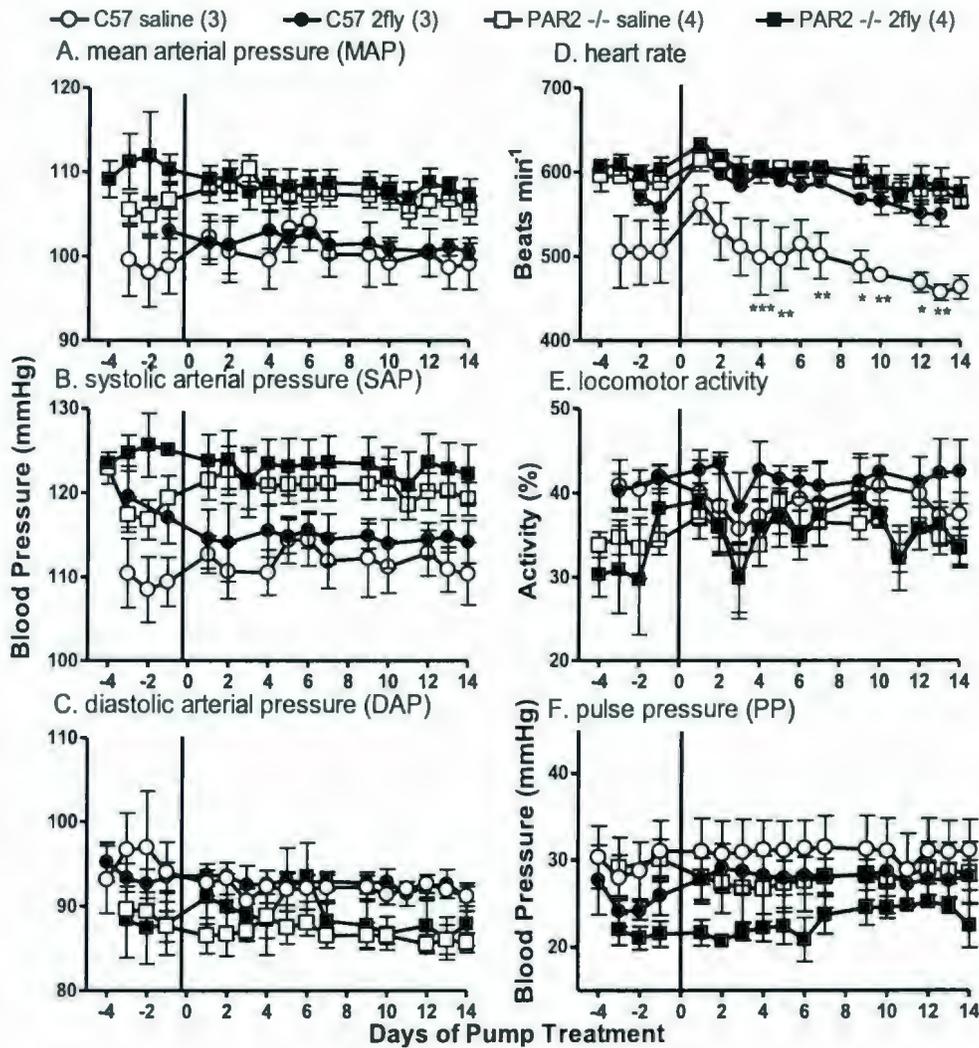
Blood pressures, heart rate and locomotor activity were measured to determine if chronic high dose PAR<sub>2</sub>-AP lowered blood pressure in mice. First, an analysis of the baseline (i.e. prior to treatments) telemetry data was performed to see if the blood pressures were different between PAR<sub>2</sub><sup>-/-</sup> and C57 mice as described previously (McGuire *et al.*, 2008). The averaged 24 h baseline data for each variable, mean arterial pressure (MAP), systolic arterial pressure (SAP), diastolic arterial pressure (DAP), heart rate (HR), pulse pressure (PP), and locomotor activity, are summarized in table 4.6. The MAP and SAP in PAR<sub>2</sub><sup>-/-</sup> were significantly higher than in C57 mice by ~7 mmHg and ~8 mmHg, respectively (P<0.05). Heart rates were about 60 beats min<sup>-1</sup> higher in PAR<sub>2</sub><sup>-/-</sup> than in C57 mice (P<0.05). A ~7% decrease in activity was measured in PAR<sub>2</sub><sup>-/-</sup> compared to C57 was also found (P<0.01). The higher baseline systolic values in PAR<sub>2</sub><sup>-/-</sup> were reported previously (McGuire *et al.*, 2008), but both the higher heart rate and lowered activity had not been observed.

During the infusion period with PAR<sub>2</sub>-AP, the averaged 24 h MAP, SAP, DAP, PP, HR and locomotor activity values were not found to be significantly different between most of the groups (P>0.05, Figure 4.12). The exception was a ~15% (100 beats min<sup>-1</sup>) lowered heart rate in C57 controls compared to C57 14 day HD PAR<sub>2</sub>-AP (P<0.05 to P<0.001 as indicated for individual treatment days; Figure 4.12D). Overall, there was no change in the mean values of the blood pressures values recorded between the treatment groups.

Given the small sample sizes in each of the groups during the treatment periods, we prepared an alternative analyses of data that would be expected to reduce the variation within groups for statistics testing. This analysis of the hemodynamic variables and locomotor activity was comprised of calculating the dependent variable change relative to the baseline periods within each group. Based on this analyses, significant decreases in systolic and pulse pressures were observed in C57 mice which were administered high dose 2fly and these pressure changes were significantly different compared to saline-treated C57 ( $P < 0.05$  to  $P < 0.001$  for different days, Figure 4.13). There were no differences in variables between  $PAR_2^{-/-}$  treatment groups (Figure 4.13). Systolic blood pressure was lowered  $\sim 7$  mmHg and pulse pressure lowered  $\sim 4$  mmHg in 2fly HD C57 compared to saline-treated C57 (Figure 4.13B and 4.13F). The other parameters were not significantly different between saline and 2fly administered mice of either strain. Therefore, blood pressure changes relative to the baseline periods were different between  $PAR_2$ -AP and saline treatments in C57, but not  $PAR_2^{-/-}$  mice.

24 hour mean variable	C57 n=6	PAR <sub>2</sub> <sup>-/-</sup> n=8	Ratio PAR2 <sup>-/-</sup> to C57
MAP (mmHg)	101.3 (2.5)	108.3 (1.5)*	1.07
SAP (mmHg)	113.5 (3.0)	122 (1.6)*	1.07
DAP (mmHg)	87.9 (2.1)	93.5 (1.9)	1.06
HR (beats min <sup>-1</sup> )	534 (24)	593 (7)*	1.11
Activity (%)	41.5 (1.3)	33.6 (1.9)**	0.81
PP (mmHg)	25.6 (2.3)	28.4 (2.0)	1.11
Offset (mmHg)	4.2 (0.8)	4.0 (0.5)	n/a

**Table 4.6. 24 h baseline hemodynamics and locomotor activity data from C57 and PAR<sub>2</sub><sup>-/-</sup> mice.** Data were recorded for baseline period for 2-4 days prior to pump implants. Values are mean (SE), n = mice/ group. Offset values indicate the calibrated value measured from implanted telemeters after surgery at 0 mmHg. n/a indicates that a ratio was not applicable for offset values. Pairwise comparisons of variables were made by Student's t-test for unpaired data. \* P<0.05 compared to C57. \*\* P<0.01 compared to C57.



**Figure 4.12. Mean 24 h hemodynamics and locomotor activity in C57 and PAR<sub>2</sub><sup>-/-</sup> during a 4 day baseline period and 14 days treatment with high dose s.c. administered 2fly. Mice were implanted with radiotelemeters 10 days prior to recording baseline (day -4 to -1), pump implant (day 0), and 14 days treatment. Parentheses, number of mice. 24 h averages of MAP, SAP, DAP, HR, activity and PP. \* P<0.05, \*\* P<0.01, \*\*\* P<0.001, C57 saline vs. C57 high dose 2fly, 2 way ANOVA, Bonferroni.**



## Chapter 5: Discussion

### 5.1 General Findings

We found that chronic *in vivo* administration of the PAR<sub>2</sub> agonist 2fly caused endothelial dysfunction in mouse aortas. This dysfunction was characterized by an attenuation of the maximum relaxations by acetylcholine that occurred in C57, but not in PAR<sub>2</sub><sup>-/-</sup> mice. This dysfunction in aortas was dose- and time-dependent given that it was observed in 7 day HD 2fly, and 14 day LD 2fly treatments. We found the effectiveness of PAR<sub>2</sub>-AP 2fly and endothelium-independent vasodilator nitroprusside were reduced in C57 after PAR<sub>2</sub>-AP treatments. Rightward shifts of 2fly CRC were caused by 7 and 14 days of LD and HD 2fly, respectively. Similarly, the reduced maximal effectiveness of nitroprusside was observed in the 14 day LD 2fly treatment group. Calcium ionophore A23187 effectiveness was not affected by the PAR<sub>2</sub>-AP treatments. Together these data indicate that PAR<sub>2</sub>-AP dysfunction was not restricted to endothelium-dependent relaxation and included endothelium-independent responses to NO.

To assess the effects of PAR<sub>2</sub>-AP treatments *in vivo* on the vascular smooth muscle signaling pathways of each agonist, we tested the same agonists activities in the presence of inhibitors of eNOS (L-NAME) or cyclooxygenases (indomethacin). Inhibition of eNOS abolished PAR<sub>2</sub>-AP and acetylcholine-induced relaxations of aortas as expected in control C57 (Al-ani *et al.*, 1995; Chataigneau *et al.*, 1999) as well as in PAR<sub>2</sub>-AP treated C57. Inhibition of eNOS did not affect nitroprusside-induced relaxations. Inhibition of cyclooxygenases did not have significant effects on acetylcholine- or

nitroprusside-induced relaxations, but did cause a rightward shift in 2fly-induced relaxations of aortas from 14 day HD 2fly C57. This rightward shift may have been the result of some COX activity present at 14 days that aided in relaxation of vessels, and thus, when inhibited a higher concentration of 2fly was needed to achieve the same relaxation. These data indicated that although NOS inhibition was sufficient to inhibit PAR<sub>2</sub>-AP induced relaxations, de novo COX activities may have been a supplementary (not critical) relaxation mechanism for PAR<sub>2</sub>-AP after 14 day HD 2fly.

An increased expression of COX in aortas of the 14 day HD C57 could have potentially explained the inhibitory effects of indomethacin on 2fly-induced relaxations. However, we found that protein expression of COX-1 and COX-2 were not significantly different between treatment groups in C57 and PAR<sub>2</sub><sup>-/-</sup>. A decreased concentration of eNOS and sGC could have explained the attenuation of ACh- and nitroprusside-induced relaxations, respectively, but we found there were no significant differences between aortas of PAR<sub>2</sub>-AP treated and saline-treated C57. We attempted to assess the expression levels and localization of PAR<sub>2</sub> by labeling sections of frozen aortas with the antibody SAM11, which was raised against the N-terminus of human PAR<sub>2</sub>. A potential change in receptor distribution would have been a potential mechanism to explain the attenuated 2fly-induced relaxations of aortas from PAR<sub>2</sub>-AP treated C57. However, under the conditions and procedures employed, specific immunofluorescence could not be attributed to PAR<sub>2</sub> receptor expression; i.e. immunofluorescence was detected in PAR<sub>2</sub><sup>-/-</sup>. While western blot data were able to exclude decreased expression in target protein

expressions of COX-1, COX-2, eNOS and sGC as possible mechanisms, the specific mechanisms causing the attenuated agonist-induced relaxations of aortas remain undetermined.

With regards to measurement of blood pressures, we found that chronic *in vivo* administered 2fly caused mild hypotension in C57 mice. This interpretation of data is supported by our finding of a significant lowering of systolic and pulse pressures as characterized by a change in these variables relative to baseline averages between saline-treated and 2fly high dose treated C57. The absolute blood pressure values that were measured directly did not clearly show any differences between the groups during the treatment periods.

## **5.2 Effects of administering chronic s.c. PAR<sub>2</sub>-AP on mouse aortas *in vitro***

Our study created a novel model of endothelium dysfunction by chronically administering PAR<sub>2</sub>-AP *in vivo*. This model is different than endothelial dysfunction models used by other researchers which measure endothelium dysfunction in many different rodent models of disease as well as in human patients (in rodents: Cameron and Cotter, 1992; Dohi *et al.*, 1991; Luscher, 1988; Luscher, 1989; Rajagopalan *et al.*, 1996; Tesfamariam *et al.*, 1989; Viridis *et al.*, 2003 and in humans: Cox *et al.*, 1989; Endemann and Schiffrin, 2004; Perticone *et al.*, 2001; Schachinger *et al.*, 2000).

In our study, acetylcholine-induced relaxation was reduced in a time- and dose-dependent manner; specifically at 7 day HD 2fly and 14 day LD 2fly in C57 mice. The lack of attenuated ACh responses after 7 days LD 2fly C57 may indicate the time effect is

related to an accumulated dose of PAR<sub>2</sub>-AP, which was reached earlier by high dose infusions. After 14 day HD 2fly, there was still a decrease in sensitivity to 2fly relative to saline-treated C57 aortas while ACh- and A23187-induced relaxations were not significantly different. This would be consistent with an interpretation that HD PAR<sub>2</sub>-AP desensitizes PAR<sub>2</sub> *in vivo*, which leads to a loss of the attenuating action on ACh- and nitroprusside-induced relaxations, and thus, resembles PAR<sub>2</sub>-AP treated PAR<sub>2</sub><sup>-/-</sup>. It was not possible to distinguish between PAR<sub>2</sub> receptor desensitization (e.g. internalization) and a potential tachyphylaxis of a downstream signal causing endothelial dysfunction.

Nitroprusside-induced relaxations of aortas were reduced in 14 day LD 2fly C57 aortas. We could not attribute a decrease in sGC to the effects of *in vivo* PAR<sub>2</sub>-AP. A deficit at the vascular smooth muscle level such as increased levels of oxidative stress, which quenches NO and thus, reduces NO bioavailability, could potentially explain both the attenuated nitroprusside- and ACh-induced relaxations of aortas in PAR<sub>2</sub>-AP treated C57. Since the 2fly-induced relaxations of aortas of 14 day HD 2fly C57 after treatment were sensitive to indomethacin, an increased level of COX could be proposed as a source of supplementary vasodilator prostanoids (e.g. prostaglandin I<sub>2</sub>). We did not find a significant difference in content of COX-1 or COX-2 in total aortic protein between treatments. However, our approach to assay whole aortic proteins would not resolve the differential over expression of COX isoforms in a cell-type specific pattern: i.e. vascular smooth muscle cells protein variation in COX expression may overshadow significant small differences in expression in endothelial cells. It is possible that indomethacin had

an off-target effect that affected 2fly-induced relaxations, but it was specific to only one treatment group. It would be worthwhile for future studies to examine the effects of reactive oxygen scavengers and selective COX-1, and COX-2 inhibitors on aortas from low dose PAR<sub>2</sub>-AP treated C57 at 14 days.

### **5.3 Effect of administering chronic s.c. PAR<sub>2</sub>-AP on hemodynamics *in vivo***

Our laboratory is the first to study the effects of chronic administered PAR<sub>2</sub>-AP on mice *in vivo*. Blood pressure data collected during the baseline period corresponds to previous work that indicated higher systolic blood pressures in PAR<sub>2</sub><sup>-/-</sup> than C57 (McGuire *et al.*, 2008). The reasons for an increased baseline systolic blood pressure in PAR<sub>2</sub><sup>-/-</sup> are attributed to the lack of PAR<sub>2</sub> and other phenotypic variations that may arise through development of these knockout mice. The anticipated hypotensive effect of PAR<sub>2</sub>-AP that was reported in acute studies with rats and mice was observed during chronic 2fly treatment in our study, but the magnitude of effect that we observed was on a much smaller scale.

Previous studies in anaesthetized mice (Cheung *et al.*, 1998) and unrestrained rats via radio telemetry (Wang *et al.*, 2010) measured reductions of 10-40 mmHg and >60 mmHg respectively. In C57 we found 2fly HD lowered the mean systolic and pulse pressures by ~7 and ~4 mmHg, respectively, relative to the baseline period. The small lowering effect of 2fly *in vivo* may be partly explained by the apparent desensitization to PAR<sub>2</sub>-AP of blood vessels. It would be expected that attenuated acetylcholine responses would be associated with higher blood pressures. In this model, it seems that the

endothelium dysfunction was small enough to be overridden by the hypotensive actions of 2fly. Nevertheless, a hypotensive effect *in vivo* of 2fly occurred despite the presence of endothelium dysfunction which suggests that PAR<sub>2</sub>-induced hypotension in the absence of endothelial dysfunction (as would occur in an acute administered dose) may be of larger magnitude (Cheung *et al.*, 1998; Damiano *et al.*, 1999; Wang *et al.*, 2010).

#### **5.4 Limitations to interpretations**

There were some limitations in this study. The first limitation is the selection of blood vessel to measure. Data in resistance vasculature such as mesenteric arteries, along with aortas (a compliance vessel), would have added to the information that was obtained and allowed a more detailed description of any results obtained. Nevertheless the relaxation actions of PAR<sub>2</sub>-AP on the aorta *in vitro* would be consistent with the isolated effect *in vivo* of PAR<sub>2</sub>-AP on systolic arterial and pulse pressures. A second limitation to the interpretations is that all of the data was obtained in males and the effect of the treatment in females was not measured. We have no reason to suggest that females would react differently to treatment, but also have no data to prove that they do not. A third limitation is in measurement of protein expression. Although there is variability in individual groups the sample size is sufficient to be confident of the results. With regards to eNOS expression a measurement of phosphorylated eNOS compared with unphosphorylated eNOS may offer an alternative interpretation about the level of eNOS activity in the two treatment groups. A fourth limitation is we do not know the concentrations of 2fly in the blood and tissues that are achieved through this

subcutaneous route. It would help in our interpretation of the blood pressure changes in relation to acute studies that administered 2fly intravenously. Knowing the final concentration in blood would allow us to titrate subcutaneous 2fly to match intravenous administration to see if chronic administration at the same dose as in these studies would elicit the large drops in blood pressures measured acutely.

## 5.5 Conclusions

Chronic *in vivo* administered PAR<sub>2</sub>-AP produced a dysfunction of vascular reactivity in mouse aortas, which was characterized by attenuated endothelium-dependent PAR<sub>2</sub> and cholinergic as well as endothelium-independent nitric oxide-mediated relaxations as expected by **Hypothesis 1** (but only at specific time and doses). The vascular dysfunction caused by high dose PAR<sub>2</sub>-AP was accompanied by significant changes in blood pressures which supported **Hypothesis 2**.

To investigate the mechanisms underlying endothelium dysfunction of aortas in this model, it may be of interest to measure the levels of inflammatory molecules in each of the treatment groups. Inflammation is known to be associated with endothelial dysfunction, and thus, pro-inflammatory mediators e.g. cytokines, may play an integral part in the changes that occur in the attenuation of endothelium-dependent and -independent induced relaxations. This chronic PAR<sub>2</sub>-AP infusion model represents an interesting approach to examining the possible connections between the activation of PAR<sub>2</sub> and the development of cardiovascular diseases involving vascular dysfunction.

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## Appendix A

#	Primer	Sequence (5' to 3')	T <sub>m</sub> (°C)
1	IMR5332 (Mutant)	GCCAGAGGCCACTTGTGTAG	64.5
2	IMR7419 (Forward)	TCAAAGACTGCTGGTGGTTG	60.4
3	IMR7420 (Reverse)	GGTCCAACAGTAAGGCTGCT	62.5

**Oligonucleotide primer sets for genotyping PAR<sub>2</sub> -/- mice. Product**

from (1) and (2) = 198 bp → mutant → neomycin gene present

Product from (2) and (3) = 345 bp → wildtype → *mPAR2 Exon 2 present*

T<sub>m</sub> represents the melting temperature for the oligonucleotides.

## Appendix B

Antibody	Relative molecular weight (kDa)	Reactivity	Catalogue #	Supplier	Dilution
rabbit anti-mouse, COX-1	70	mouse, Rat	160109	Cayman	1:800
goat anti-mouse, COX-2	70	mouse, rat, human	sc-1745	Santa Cruz	1:1000
rabbit anti-mouse, GAPDH-FL	37	mouse, rat, human	sc-25778	Santa Cruz	1:1000
goat anti-rabbit IgG HRP linked			10004301	Cayman	1:10000
donkey anti-goat IgG HRP linked			sc-2020	Santa Cruz	1:5000
rabbit anti-sGC	69	mouse	ab50333-100	Abcam	1:7500
mouse anti-eNOS	140	mouse, rat, human	610296	BD Transduction Lab.	1:7500
goat anti-rabbit IgG HRP linked			PI-1000	Vector	1:10000
horse anti-mouse IgG HRP linked			PI2000	Vector	1:10000

**Antibodies used in western blot analysis.** HRP, horseradish peroxidase.

