Koeners, M. P., Lewis, K. E., Ford, A. P., & Paton, J. F. (2016). Hypertension: A problem of organ blood flow supply-demand mismatch. Future Cardiology, 12(3), 339-349. https://doi.org/10.2217/fca.16.5
Hypertension: A problem of organ blood flow supply-demand mismatch

Word count: 4292

Maarten P. Koeners¹, Kirsty E. Lewis¹, Anthony P. Ford², Julian F.R. Paton¹

¹School of Physiology, Pharmacology & Neuroscience, Biomedical Sciences, University of Bristol, Bristol, UK

²Afferent Pharmaceuticals, San Mateo, CA, USA

Dr Maarten Koeners

School of Physiology, Pharmacology & Neuroscience

Medical Sciences, Building, University of Bristol, Bristol, UK

m.koeners@bristol.ac.uk

+44 (0)117 33 11629
Abstract

This review introduces a new hypothesis: that sympathetically mediated hypertensive diseases are caused, in most part, by the activation of visceral afferent systems that are connected to neural circuits generating sympathetic activity. We consider how organ hypoperfusion and blood flow supply-demand mismatch might lead to both sensory hyper-reflexia and aberrant afferent tonicity. We discuss how this may drive sympatho-excitatory positive feedback and extend across multiple organs initiating, or at least amplifying sympathetic hyperactivity. The latter, in turn, compounds the challenge to sufficient organ blood flow through heightened vasoconstriction that both maintains and exacerbates hypertension.

Keywords: hypoperfusion, organ blood flow, visceral afferent hyper reflexia, hypertension, sympathetic hyperactivity
Overview

Causes of elevated sympathetic activity in neurogenic hypertension remain enigmatic. We explore evidence to support the notion of blood flow supply-demand mismatch to an organ as a factor involved in the initiation of raised sympathetic activity, and its subsequent amplification, in hypertension. We first consider some homeostatic mechanisms regulating blood flow and then discuss emerging changes that may occur during the development of hypertension that sensitize afferent innervation of target organs. We hypothesize that activation of visceral afferent systems induces increases in sympathetic nerve activity (SNA) that can initiate and sustain hypertension. We term this, the visceral afferent activation hypothesis of hypertension.

Physiological mechanisms ensuring organ blood flow homeostasis: a brief overview

All organs have a capacity to increase blood flow through local functional (reactive) hyperaemia, autoregulatory, endocrine and neural mechanisms. Blood flow autoregulation is defined as the ability of an organ to maintain a constant blood flow despite either increases or decreases in blood (perfusion) pressure. Blood flow autoregulation is intrinsic to the arterioles within the organ and occurs in the absence of neural and hormonal influences. Endocrine controls include epinephrine and norepinephrine, as well as vasopressin, the renin-angiotensin-aldosterone system (RAAS), atrial natriuretic peptide, and erythropoietin. Neural mechanisms include baroreceptors in the aorta, carotid sinuses and right atrium, and peripheral and central chemoreceptors that monitor blood levels of oxygen, carbon dioxide, and hydrogen ions;
together these systems modulate levels of autonomic and hormonal activity through central reflex arcs coursing through various inter-connected central nervous system structures. Such structures also bring about blood flow homeostasis during stress, hyperosmolarity, emotion, fear and anxiety. In physiological conditions, the aforementioned homeostatic mechanisms will distribute blood flow, and hence oxygen, to organs in proportion to their metabolic demand, which is precisely controlled [1]. Normally, oxygen delivery exceeds the rate of oxygen consumption (demand) safeguarding capacity within each organ, which can be tapped into as a change in state demands [1]. For example, upon ascending to high altitude or during exercise, blood flow is increased to maintain a preferred supply/demand ratio [1]. However, if demand outstrips supply (i.e. a blood flow supply-demand mismatch), then hypoxic-hypoperfusion results. This might be corrected by increasing perfusion pressure, perhaps evoked through excitation of the organ’s own afferent system. However, according to Poiseuille’s law, at constant perfusion pressure blood flow is directly proportional to the fourth power of the radius of the vessel, meaning that a proportionally large increase in blood pressure will be needed to restore blood flow if the radius decreases i.e. the resistance increases. Blood pressure can be elevated by increasing either cardiac output and/or vascular resistance through activation of a neurohumoral mechanism including vasomotor sympathetic activity. Once the organ oxygen demand returns to basal levels, haemodynamic homeostasis is restored. However, if organ hypoxic hypoperfusion persists, or if the afferent circuits from that organ convey signals of such condition, even if aberrantly once it has passed, we surmise that this may result in augmented sympathetic discharge and thus hypertension. It has been maintained that most forms of
hypertension are associated with increased total peripheral resistance (TPR), rather than increased cardiac output [2]. In such conditions, increased SNA in both men and older women is a primary driver of increased TPR [3]. Chronic elevation of TPR as a mechanism to increase blood pressure may reduce organ blood flow capacity thereby increasing the vulnerability to tissue hypoxic-hypoperfusion. Since all organs are innervated by sensory nerves, we propose that organ hypoperfusion will activate afferent activity and reflexively stimulate sympathetic hyperactivity leading to hypertension. However, this generalised vasoconstriction may compromise blood flow to other organs and thus trigger blood flow a broad supply-demand mismatch, which may result in the recruitment of additional afferent drivers that compound the hypertensive state. We explore this cycle of maladaptation in more detail giving examples to substantiate this notion.

The sympathetic problem of hypertension

Unequivocal evidence supports chronic activation of the sympathetic nervous system as a characteristic of hypertension and its participation in the initiation, maintenance and progression of blood pressure in experimental animal and human studies [4]. A big clinical challenge is to unveil the cause(s) of sympathetic over-activation and design novel therapies that lower it below its threshold for triggering significant increases in TPR. Evidently, sympathetic hyperactivity interacts with many pathologies beyond neurogenic hypertension, including heart failure, salt sensitivity, obesity, glucose intolerance, rheumatoid arthritis and many more. However, the aim of our review is to understand the
relationship between organ hypoperfusion and subsequent visceral afferent activation as a potential driver of sympathetically mediated hypertension.

Visceral afferent hyperactivity: consequences for sympathetic activity and organ blood flow

To the best of our knowledge, all organs are connected to the brain reciprocally by visceral afferent and efferent nerves (Fig. 1). Many of these afferent nerves can trigger sympatho-excitatory responses through spinal and supra-spinal reflexes. Exceptions include baroreceptors, right atrial and pulmonary stretch receptors and some renal afferents that inhibit sympathetic activity and may oppose hypertension-induced sympathetic hyperactivity [5]. Interestingly, these receptors are mechanosensory and de-activated by hypoperfusion and/or metabolic stimuli so may not be relevant to blood flow supply-demand mismatch [5]. We propose that metabolite-sensitive afferents (metabosensors) that trigger sympathetic activity responses are less susceptible to de-sensitisation (adaptation) and, under pathophysiological conditions, can: (i) become sensitized, producing exaggerated reflex responses (hyperreflexia) and, (ii) generate aberrant tone (hypertonicity); the latter has the potential to provide a sustained drive for maintaining high levels of sympathetic activity (Fig. 1). Their activation may actively depress sympato-inhibitory reflexes, such as the arterial baroreceptor reflex. Evidence supporting the presence of excessive afferent signalling in hypertension comes from the kidney [6,7] and carotid body [8-11] as their selective denervation can reduce both sympathetic activity and blood pressure, as we discuss later.
It is important to recognise that physiological afferent signalling from an organ may occur in response to stimulants released locally because of a change in metabolic demand. Such examples include: reduced blood flow and hypoxia, hypercapnia, and metabolic stress. Functional or reactive hyperaemia in skeletal muscle is a mechanism that equates the change in metabolic demand with increases in blood flow. The metabolites leached from respiring tissues cause localized vasodilatation but, at sufficient concentration, also stimulate afferent endings (group III or IV fibers). The latter results in reflex increases in sympathetic activity and arterial pressure, with the sole aim of increasing perfusion to the muscle bed from which the afferents were activated. Functional hyperaemia normally offsets sympathetically mediated vasoconstriction [12]. The net result is elevated blood flow to the metabolically active organ to satiate its increased demand for oxygen. The increased perfusion also serves to washout metabolites, reduce their accumulation and may temper afferent activity to a level that optimises oxygen supply and demand; hence an optimal equilibrium is reached. Afferent signalling normally ceases once oxygen supply outstrips demand. However, in disease states such as hypertension, afferent signalling may become exaggerated and persist even in the absence of metabolites. Further, local metabolites mediating the vasodilatation may be less effective at opposing high levels of sympathetically mediated vasoconstriction [13] [14]. Indeed, in hypertension, nitric oxide did not attenuate sympathetic vasoconstriction during exercise; an effect seen in animals with normal blood pressure [13]. We discuss these possibilities below.

Sensitisation of afferent feedback generating sympathetic excess in hypertension
Sympathetic activation patterns may be graded and/or differentially controlled on an organ basis. For example, the classic ‘defence’ or ‘alerting’ response is characterized by increases in arterial pressure and heart rate with vasodilatation in skeletal muscle (mediated, in part, by sympatho-inhibition), and vasoconstriction in the splanchnic, renal and cutaneous vascular beds [15]. Our notion is that in conditions of hypertension there is an underlying imbalance, with vasodilatory metabolites giving way to a predominance of sympathetic vasoconstrictor influence that is driven by afferent sensitization and emergence of aberrant afferent tonicity. The mechanism(s) involved in afferent sensitisation and tone generation remain an open question and may be organ- and state-dependent but could result as a consequence of hypoxic-hypoperfusion triggering transcriptional processes. We propose that a plethora of initiators/mediators could be involved in this sensitisation, including metabolic stressors (hypoxia, hypercapnia, hyperglycemia, ATP, potassium ions, low pH), oxidative stress, anatomical anomalies (preconditioned, congenital), anaemia, respiratory stress, atherosclerotic plaque, inflammation and RAS activation. These mediator(s) themselves may sensitise the very mechanisms that cause depolarisation and trigger receptor potentials in afferent endings resulting in a chronic excitatory effect. Important to our hypothesis is that aberrant afferent firing persists at rest in the absence of any metabolic stimuli, and thus is a pathological signal. The latter is highly relevant as at rest there will be an absence of opposing vasodilatory metabolites making sympathetically mediated vasoconstriction more intense, worsening the problems of hypoperfusion and hypertension. Through a vicious circle the latter would result in further stimulation of afferent activity and reflexively evoked sympathetic vasoconstriction accentuating the problem of blood flow supply-
demand mismatch. We do not rule out a cross-talk mechanism whereby sympathetic activity itself sensitises adjacent afferent endings as an additional amplifying mechanism; there is at least anatomical evidence for this in the kidney where afferents and sympathetic fibres are intertwined [16]. Highly analogous is somatosensory sensitization seen in states of “sympathetically-maintained pain” or reflex sympathetic dystrophy, now thought of as “complex regional pain syndrome”. These are chronic pain conditions associated with sympathetic sprouting onto primary afferents terminals, dorsal root ganglion and spinal dorsal horn afferent terminals [17]. Being released by sympathetic postganglionic neurones, ATP participates in this sensitisation [18]. We propose that the same process of sensitization may apply to visceral afferent activation of hypertension.

Heightened activation of the sympathetic nervous system through aberrant afferent tonicity from an organ may offset the vasodilatation produced by functional hyperaemia. For example, abnormal muscle afferent signalling in heart failure patients increased the passive leg movement-induced increases in norepinephrine spillover and arterial blood pressure, which significantly reduced femoral blood flow, oxygen delivery, and tissue oxygen saturation [19]. If sympathetically mediated vasoconstriction becomes widespread across vascular beds this may recruit multiple sympatho-excitatory afferent systems and amplify the problem of raised blood pressure (Fig. 1). Additionally, autoregulation in response to the rising perfusion pressure will also increase vascular resistance in an attempt to maintain constant blood flow but at the expense of further elevating TPR. Moreover, persistent and heightened sympathetic activity may reset autoregulation to higher pressure levels (e.g. renal blood flow autoregulation curve is
shifted to a higher range of renal arterial pressures in hypertensive dogs with enhanced sympathetic activity [20]) as well as cause arteriolar re-modelling[21]; this would have deleterious consequences for blood flow supply-demand matching. Finally, it is also likely that hypoxic-hypoperfusion and reduced blood flow become greatly agonized at night when blood pressure normally dips [22]. In a constant state of sympathetic overactivity it is easy to see how nocturnal dipping is lost in conditions of hypertension [23]. Below we consider some examples of organs exhibiting excessive afferent activity and heightened SNA in hypertension.

Potential sources of afferent hyperactivity

Although it seems that many, if not all, organs affect blood pressure regulation we will focus within this review on the organs that we consider as exemplary of our hypothesis and where evidence exists supporting organ hypoperfusion and blood flow supply-demand mismatch triggering dysfunctional afferent activity and reflexively driven sympathetic activity.

(i) Kidney afferents and hypertension

Renal afferent nerves primarily terminate peripherally in the renal pelvis and project to the spinal cord with onward transmission to the nucleus tractus solitarii (NTS), rostral ventrolateral medulla (RVLM), subfornical organ and paraventricular nucleus (PVN). There are single modality fibres (mechanoreceptors) that sense stretch of the pelvic wall causing sympatho-inhibition, chemo-sensitive receptors causing sympatho-activation,
and multimodal fibres that sense both (reviewed in [24]). Neurally mediated responses occurring in one kidney as a result of interventions on the same or opposite kidney have been defined as reno-renal reflexes, which function to decrease renal efferent SNA to minimize sodium retention [25]. However, in ischemic/hypoxic kidneys and/or in the hypertensive state there is a reversal of the reno-renal reflex: stimulation of afferent nerves by ischemic metabolites such as adenosine, and/or by uremic toxins such as urea [26] enhances the sympatho-excitatory state, increases salt retention and blood pressure. This reversal of the reno-renal reflex is significant since afferent signals emanating from the kidney to the central nervous system have been strongly associated with the aetiology of hypertension. Indeed in experimental animal models of hypertension the removal of the afferents by either dorsal rhizotomy [7,27-29] or specific inhibition of afferent fibers by capsaicin treatment [6] have proven to be anti-hypertensive. Interestingly, Cowley et al [30] has demonstrated that the reduction of the blood flow to the medulla, a mildly hypoxic area of the kidney, leads to hypertension and renal injury when either a pharmacologically induced or a naturally occurring imbalance of the normal redox state. This support the concept of oxidative stress as an initiator/mediator involved in hypertension, potentially via hypoxia-hypoperfusion and afferent sensitization. Recent clinical trials have shown that blood pressure and SNA are both reduced after bilateral denervation (afferent and efferents) of the kidneys in some drug-resistant hypertensive patients [31-33], although the efficacy of this intervention is debated [34]. Recently, it has emerged that afferents are important for the hypertensive state in chronic kidney disease [35]. Future studies are needed to understand the mechanisms for renal afferent sensitisation and tonicity in hypertensive patients; putative stimulants are discussed
Hypothetically, understanding the latter may provide an effective means to select patients most likely to respond to treatment (pharmacological or denervation). Taken together, these data emphasize the role of afferent signals emanating from the kidney in the generation of hypertension.

In recent years, evidence has accumulated that kidney hypoxia plays a significant role in the pathogenesis and progression of renal disease [36-39]. Even a small lesion in the kidney, resulting in an area(s) of ischaemia not necessarily affecting renal function, can cause hypertension, perhaps via afferent activation [40]. Renal hypoperfusion, ischaemia and hypoxia can all trigger afferent signalling to reflexively elevate sympathetic activity and arterial pressure. This has led to the prediction that renal hypoxia is not just a consequence of kidney disease, but rather a primary pathogenic event [36-38,41-47]. But what could be the initial trigger? Exogenous administration of angiotensin-II (AngII) can lead to hypoperfusion of post-glomerular peritubular capillaries, and subsequent hypoxia within the tubules and interstitial space [39] [48]. We propose that hypertensive kidney disease is driven by vicious loops of positive feedback, initiated by increased AngII triggered by hypoperfusion and accompanied by nephron loss, inflammation and diabetes. This results in oxidative stress and nitric oxide deficiency augmenting hypoperfusion and renal afferent signalling. Therefore, improving blood perfusion and thus oxygenation of the kidneys may reduce SNA and arterial pressure and improve renal function, thereby providing a novel future treatment strategy. This is supported by the findings that: (i) pharmacologically increasing renal oxygen consumption per se caused renal hypoxia, proteinuria [49] and eventually leads to renal injury [50] and, (ii) application
of 100% oxygen to patients with chronic kidney disease reduced muscle SNA, whereas such an intervention did not affect muscle SNA in control patients [51]. This mismatch in renal oxygen demand and supply exemplifies how afferent driven sympatho-excitatory is a powerful stimulus for hypertension.

(ii) Carotid Body afferents and hypertension

Stimulation of the carotid body (CB), the dominant peripheral chemoreceptor, drives sympathetic tone through relatively direct signalling to the NTS, RVLM and PVN resulting in increased blood pressure [52,53]. In cardiovascular diseases, it appears that the CB generates aberrant afferent discharge [8,9]. Schultz et al. have clearly implicated a significant role of CB afferent drive in the sympathetic hyperactivity and breathing dysregulation in animal models of chronic heart failure (CHF) [54,55]. Blood flow to the CB is exceptionally high in relation to tissue mass in health [56] but in rabbits with pacing induced chronic heart failure this was reduced due to lowered cardiac output [55]. This might account for CB afferent tonicity. Given this, one might predict that lowering CB afferent drive should be therapeutically beneficial. As a proof of principle CB resection was performed in heart failure patients and partially corrected cardiac autonomic balance and cardiac baroreflex gain [10,11], and reduced muscle sympathetic activity. Moreover, the CB is an afferent source driving sympathetically mediated hypertension in the spontaneously hypertensive rat (SHR) [8,9]. Again CB chemoreceptors are tonically active in the SHR [8,9] and their dis-connection from the brain is antihypertensive, substantially reduces renal sympathetic activity, and improved both baroreflex and renal function [8,9]. Intriguingly, there was an additive blood pressure lowering effect when
renal denervation was subsequently performed [9]. These data strongly support our hypothesis that organ hypoperfusion and blood flow supply-demand mismatch recruits additional sources of afferent drive across organs with each independently contributing to sympathetic excess and hypertension (Fig. 1).

(iii) Skeletal muscle afferents and hypertension

Sympathetic engagement during exercise is initiated, in part, by activation of thin fiber afferents arising from contracting skeletal muscle. In the case of lower limb muscles these project via the lumbar dorsal horn of the spinal cord and via supra-spinal circuits modulate cardiovascular and respiratory activity and their reflex control [57]. These afferents are mechanically (mechanoreceptor; type III sensory fibres) and/or metabolically sensitive (metaboreceptor; type IV fibres). During the onset of exercise these afferents become activated and evoke the ‘exercise pressor response’ consisting of rises in arterial pressure, heart rate, stroke volume, cardiac output, redistribution of blood flow to active skeletal muscle and hyperventilation [58]. What evidence exists that these afferents become tonically active in the hypertensive state? In hypertension, sensitisation of both mechanically and metabolically sensitive skeletal muscle afferents has been demonstrated [59,60]. Moreover, the exercise pressor response is augmented and associated with the development of hypertension [61]. In chronic heart failure this includes an increased sensitivity of type 3 fibres compared to type 4 and heightened P2X response [62]. Functional sympatholysis, the process whereby sympathetic vasoconstriction is offset by metabolites released from the exercising skeletal muscle, is impaired substantially in hypertension [63]; this results in reduced oxygenation and blood flow in
exercising muscles of hypertensive individuals compromising their ability to exercise [63].

This, presumably, leads to persistent afferent activation and hyperreflexia producing exaggerated pressor responses during exercise but may also contribute to reduced exercise tolerance through fatigue and possibly pain.

There are a wide range of molecules involved in the regulation of blood flow to skeletal muscle during exercise. One major example is adenosine triphosphate (ATP). ATP, a potent vasodilator, stimulates the formation of both nitric oxide and prostaglandins [64], which counteract local sympathetic vasoconstriction [65,66]. A further source of nitric oxide production is by mechanically induced signals, including shear stress activated endothelial nitric oxide synthase [67]. Recent studies have shown that oxidative stress further increases vasoconstriction in skeletal muscle in rats with induced hypertension [68-70], suggesting a reduction/absence of the opposing dilatatory influence of nitric oxide. Taken together, this supports our hypothesis of organ hypoperfusion and blood flow supply-demand mismatch and afferent sensitisation from a relatively large vascular bed that can drive neurogenic hypertension (Fig. 1).

(iv) Other contributing afferents and cross talk

Stimulation of intestinal mechanoreceptors (stretch) or chemoreceptors activates splanchnic nerve afferents resulting in decreases in tissue blood flow in the splanchnic organs (duodenum, jejunum, pancreas, spleen, stomach and liver) and kidneys [71]. This is most likely to be mediated by the sympathetic nervous system since electrical stimulation of intestinal afferents increases sympathetic activity in the splanchnic bed [71].
On the other hand, sympatho-inhibition occurs following the ingestion of a meal. This can augment splanchnic blood flow by approximately 150% above baseline, postprandially [72]. In hypertensive subjects blood flow to the splanchnic vascular bed is reduced [72], while in obese, hypertensive Sprague–Dawley rats the postprandial sympatho-inhibition and vasodilator effects are abolished. Although this does not separate cause from consequence it does indicate a connection between splanchnic hypoperfusion, reduced sympatho-inhibition and hypertension.

High blood pressure can induce vascular (arterial/arteriole) hypertrophy [73], as can the increase in sympathetic nervous activity that is associated with hypertension [74-76]. Lumen narrowing, stiffening and exacerbated responses to sympathetic nervous system stimulation may all contribute to elevations in vascular resistance and the hypertensive condition. However, there is also evidence that the arterial re-modelling can occur before the development of hypertension as a congenital mechanism in the spontaneously hypertensive rat (SHR) [77].

Activation of hepatic afferent nerves causes a decrease in blood flow through the hepatic artery again mediated by sympathetic nerves [78]. Activation of spinal cardiac afferents also increases sympathetic activity within minutes [79] and impairs baroreflex control of renal sympathetic nerve activity in rats [79]. Conceptually this positive feedback can correct hypoperfusion of cardiac tissue thereby reducing the severity of ischemia and decreasing infarct-size in myocardial ischemia injury. As mentioned above, cross talk between sympathetic and afferent fibres could be a part of a potential mechanism for
sensitisation and afferent aberrant discharge as noradrenaline can activate sensory receptors directly [16], and ATP is co-released with NA from sympathetic post-ganglionic efferents [80] and further activates C-fibers. Indeed, there is histological evidence of close coupling between efferent and afferent C-fibres in human skin [81] and Kopp et al. have shown that there is a close apposition of afferent and efferent nerves in the renal pelvis [16]. Finally, activation of the sympathetic supply to the carotid body causing vasoconstriction [82] could also account for its sensitisation and aberrant tone in hypertension.

The selfish brain hypothesis of hypertension

Cushing's response is enunciated as a physiological nervous system response to increased intracranial pressure that results in Cushing's triad of increased blood pressure, irregular breathing, and a reduction of heart rate. Paton et al. have proposed that the 'Cushing Mechanism' is not just a 'last ditch' protection for critically ischaemic brain but 'a physiological mechanism .... and key regulator of blood pressure' [83]. This is supported by the observation that that in humans high blood pressure levels correlate with increased vertebral artery resistance [83,84]. Thus, could perfusion of the brain be a determinant of the set point of arterial pressure and is brainstem hypoperfusion a contributing mechanism in neurogenic hypertension? In support of this, increasing cerebral artery vascular resistance activates the sympathetic nervous system in rats [76]. Further, Cates et al. have demonstrated that vertebral artery narrowing, increased vertebral artery resistance, a shift to anaerobic metabolism within the brainstem and an exaggerated sympatho-excitatory response to reduced cerebral perfusion all occur prior
the onset of hypertension in spontaneous hypertensive rats [85]. Tissue oxygen levels in
the spontaneously hypertensive rat were found to be 15 mmHg lower than in a
normotensive rat at the same level of arterial pressure [86]. The transduction mechanism
is unknown but could include a central detector of hypoxia, an “intra-cranial baroreceptor”,
ion-channels sensitive to blood flow or shear stress, [85] and may involve ATP and
lactate [86]. For example, both traumatic and non-traumatic brain injury can result in
paroxysmal sympathetic hyperactivity and hypertension [87].

**Future perspective**

Although many hypertensive drugs have a degree of penetrance into the brain, targeting
the central nervous system with drugs causes poorly tolerated side effects and triggers a
major clinical challenge of poor patient compliance to medication. According to our
hypothesis, we need to consider targets within the peripheral nervous system and identify
those visceral afferents that have become sensitised and tonically activated in
hypertension. Establishing the molecular mechanisms for this afferent tonicity would then
allow selective drugs (that need not cross the blood brain barrier) to temper their aberrant
discharge. An ideal treatment would be a drug that targets a defined organ with known
aberrant activity and blocks this pathological signalling while preserving the physiological
operation of the afferent system. For example, selective blockade of purinergic receptor
subtype (P2X3) abolished chronic pathological cough but defensive coughing (such as
that evoked following aspiration) was preserved [88]. Reducing organ hypoxic-
hypoperfusion and improving organ blood flow and oxygen reserve/capacity is another
considered approach for treating hypertension. Experimental evidence shows that intra-
renal renin-angiotensin-system (RAS) is compartmentalized from the systemic RAS such that intrarenal angiotensin converting enzyme (ACE) is not adequately inhibited by plasma concentrations of ACE inhibition in currently used dosages [89]. Given that angiotensin II can cause renal hypoxia and hypertension (see above), RAS inhibition selectively within the kidney may ameliorate hypoxic-hypoperfusion and reduce sympathetic hyperactivity. Furthermore activation of hypoxia inducible factors (HIF-1α and HIF-2α) has been demonstrated to protect kidneys from hypoxia and progressive injury [90] by making the kidneys less sensitive to hypoxic-hypoperfusion. Notably, the efficacy of HIF activation appears to depend on when it is administered during hypertensive kidney disease [91] stressing the importance of timing relative to disease progression. Taken together, we propose that organ blood flow supply-demand mismatch could be a target for treating the sympathetic hyperactivity in hypertension. The future challenge is to off-set arteriolar vasoconstriction, increase organ blood flow and replenish the blood flow and oxygen supply of specific bodily organs.
Executive summary

• In physiological conditions blood flow is distributed to all organs in proportion to local oxygen/energy demand.

• Blood flow demand can outstrip supply bringing about hypoxic-hypoperfusion especially when vasodilatory mechanisms are compromised.

• Aberrant afferent signalling from an organ may occur in response to hypoperfusion or unmet oxygen demand.

• Afferent sensitisation can lead to excessive reflexively evoked sympathetic vasoconstriction, hypoxic-hypoperfusion and reduced blood flow that leads to further activation of afferent activity.

• Recent clinical trials have shown anti-hypertensive potency of: i) bilateral renal nerve denervation in some drug-resistant hypertensive patients and ii) carotid body afferent denervation in heart failure patients.

• Hypertension is associated with an exaggerated exercise pressor response and we propose sensitisation and aberrant discharge from skeletal muscle afferents contribute to excessive sympathetic activity.

• The brain stem may detect blood flow directly thereby acting as a central nervous system determinant of the set point of vasomotor sympathetic tone and contribute to sympathetic excess in the hypertensive condition if it becomes hypoperfused.

• We propose that organ blood flow supply-demand mismatch is a major source of visceral afferent drive and can extend across organs contributing to sympathetic excess and hypertension, a process that is exacerbated during nocturnal blood pressure dipping.
References

1. Wolff C. Colloid Supplementation during Induction of Anesthesia. *Emergency Medicine*, 1(2), 1000EOMJ1108 (2015).
2. Mayet J, Hughes A. Cardiac and vascular pathophysiology in hypertension. *Heart*, 89(9), 1104-1109 (2003).
3. Hart EC, Charkoudian N. Sympathetic neural regulation of blood pressure: influences of sex and aging. *Physiology*, 29(1), 8-15 (2014).
4. Esler M, Lambert E, Schlaich M. Point: Chronic activation of the sympathetic nervous system is the dominant contributor to systemic hypertension. *Journal of applied physiology*, 109(6), 1996-1998; discussion 2016 (2010).
5. Hines T, Toney GM, Mifflin SW. Responses of neurons in the nucleus tractus solitarius to stimulation of heart and lung receptors in the rat. *Circulation research*, 74(6), 1188-1196 (1994).
6. Foss JD, Wainford RD, Engeland WC, Fink GD, Osborn JW. A novel method of selective ablation of afferent renal nerves by periaxonal application of capsaicin. *American journal of physiology. Regulatory, integrative and comparative physiology*, 308(2), R112-R122 (2015).
7. Campese VM, Kogosov E. Renal afferent denervation prevents hypertension in rats with chronic renal failure. *Hypertension*, 25(4 Pt 2), 878-882 (1995).
8. Abdala AP, McBryde FD, Marina N et al. Hypertension is critically dependent on the carotid body input in the spontaneously hypertensive rat. *The Journal of physiology*, 590(Pt 17), 4269-4277 (2012).
9. McBryde FD, Abdala AP, Hendy EB et al. The carotid body as a putative therapeutic target for the treatment of neurogenic hypertension. *Nature communications*, 4, 2395 (2013).
10. Niewinski P, Janczak D, Rucinski A et al. Carotid body removal for treatment of chronic systolic heart failure. *International journal of cardiology*, 168(3), 2506-2509 (2013).
11. Niewinski P, Janczak D, Rucinski A et al. Dissociation between blood pressure and heart rate response to hypoxia after bilateral carotid body removal in men with systolic heart failure. *Experimental physiology*, 99(3), 552-561 (2014).
12. Joyner MJ, Casey DP. Regulation of increased blood flow (hyperemia) to muscles during exercise: a hierarchy of competing physiological needs. *Physiological reviews*, 95(2), 549-601 (2015).
13. Zhao W, Swanson SA, Ye J et al. Reactive Oxygen Species Impair Sympathetic Vasoregulation in Skeletal Muscle in Angiotensin II-Dependent Hypertension. *Hypertension*, (2006).
14. Thomas GD. Functional sympatholysis in hypertension. *Autonomic Neuroscience*, 188, 64-68 (2015).

* Describes an exciting new methodology to specificity abolish renal afferent activity.
** A classic paper on experimental renal denervation in hypertension and kidney disease.
* Outlines the role and possible of the carotid body in neurogenic hypertension.
** Outlines the role and possible therapeutic target of the carotid body in neurogenic hypertension.
* Classic paper on neural control of kidney function.
15. Hilton SM. Ways of viewing the central nervous control of the circulation--old and new. *Brain research*, 87(2-3), 213-219 (1975).

16. Kopp UC, Cicha MZ, Smith LA, Mulder J, Hokfelt T. Renal sympathetic nerve activity modulates afferent renal nerve activity by PGE2-dependent activation of alpha1- and alpha2-adrenoceptors on renal sensory nerve fibers. *American journal of physiology. Regulatory, integrative and comparative physiology*, 293(4), R1561-1572 (2007).

17. Schlereth T, Drummond PD, Birklein F. Inflammation in CRPS: role of the sympathetic supply. *Autonomic neuroscience : basic & clinical*, 182, 102-107 (2014).

18. Ford AP. In pursuit of P2X3 antagonists: novel therapeutics for chronic pain and afferent sensitization. *Purinergic Signal*, 8(Suppl 1), 3-26 (2012).

19. Ives SJ, Amann M, Venturelli M et al. The Mechanoreflex and Hemodynamic Response to Passive Leg Movement in Heart Failure. *Med Sci Sports Exerc*, (2015).

20. Iversen BM, Kvam FI, Matre K, Ofstad J. Resetting of renal blood autoregulation during acute blood pressure reduction in hypertensive rats. *The American journal of physiology*, 275(2 Pt 2), R343-349 (1998).

21. Renna NF, de Las Heras N, Miatello RM. Pathophysiology of vascular remodeling in hypertension. *Int J Hypertens*, 2013, 808353 (2013).

22. Koroboki E, Manios E, Psaltopoulou T et al. Circadian variation of blood pressure and heart rate in normotensives, white-coat, masked, treated and untreated hypertensives. *Hellenic J Cardiol*, 53(6), 432-438 (2012).

23. Sherwood A, Steffen PR, Blumenthal JA, Kuhn C, Hinderliter AL. Nighttime blood pressure dipping: the role of the sympathetic nervous system. *American journal of hypertension*, 15(2 Pt 1), 111-118 (2002).

24. Johns EJ, Kopp UC, DiBona GF. Neural control of renal function. *Comprehensive Physiology*, 1(2), 731-767 (2011).

25. Kopp UC. Role of renal sensory nerves in physiological and pathophysiological conditions. *American journal of physiology. Regulatory, integrative and comparative physiology*, 308(2), R79-R95 (2015).

26. Katholi RE. Renal nerves and hypertension: an update. *Federation proceedings*, 44(13), 2846-2850 (1985).

27. Ye S, Ozgur B, Campese VM. Renal afferent impulses, the posterior hypothalamus, and hypertension in rats with chronic renal failure. *Kidney Int*, 51(3), 722-727 (1997).

28. Campese VM, Kogosov E, Koss M. Renal afferent denervation prevents the progression of renal disease in the renal ablation model of chronic renal failure in the rat. *Am J Kidney Dis*, 26(5), 861-865 (1995).

29. Kopp UC, Cicha MZ, Smith LA. Dietary sodium loading increases arterial pressure in afferent renal-denervated rats. *Hypertension*, 42(5), 968-973 (2003).

30. Cowley AW, Jr., Abe M, Mori T, O'Connor PM, Ohsaki Y, Zheleznova NN. Reactive oxygen species as important determinants of medullary flow, sodium excretion, and hypertension. *American journal of physiology. Renal physiology*, 308(3), F179-197 (2015).
31. Krum H, Schlaich M, Whitbourn R et al. Catheter-based renal sympathetic denervation for resistant hypertension: a multicentre safety and proof-of-principle cohort study. *Lancet*, 373(9671), 1275-1281 (2009).

32. Esler MD, Krum H, Sobotka PA, Schlaich MP, Schmieder RE, Bohm M. Renal sympathetic denervation in patients with treatment-resistant hypertension (The Symplicity HTN-2 Trial): a randomised controlled trial. *Lancet*, 376(9756), 1903-1909.

33. Schlaich MP, Hering D, Sobotka PA, Krum H, Esler MD. Renal denervation in human hypertension: mechanisms, current findings, and future prospects. *Curr Hypertens Rep*, 14(3), 247-253 (2012).

* Important paper demonstrating renal hypoxia precedes renal pathology.

34. Bhatt DL, Kandzari DE, O’Neill WW et al. A controlled trial of renal denervation for resistant hypertension. *The New England journal of medicine*, 370(15), 1393-1401 (2014).

35. Salman IM. Cardiovascular Autonomic Dysfunction in Chronic Kidney Disease: a Comprehensive Review. *Current hypertension reports*, 17(8), 59 (2015).

36. Heyman SN, Khamaisi M, Rosen S, Rosenberger C. Renal parenchymal hypoxia, hypoxia response and the progression of chronic kidney disease. *Am J Nephrol*, 28(6), 998-1006 (2008).

37. Legrand M, Mik EG, Johannes T, Payen D, Ince C. Renal hypoxia and dyoxia after reperfusion of the ischemic kidney. *Mol Med*, 14(7-8), 502-516 (2008).

38. Tanaka T, Kato H, Kojima I et al. Hypoxia and expression of hypoxia-inducible factor in the aging kidney. *J Gerontol A Biol Sci Med Sci*, 61(8), 795-805 (2006).

39. Manotham K, Tanaka T, Matsumoto M et al. Evidence of tubular hypoxia in the early phase in the remnant kidney model. *Journal of the American Society of Nephrology : JASN*, 15(5), 1277-1288 (2004).

40. Campese VM. A new model of neurogenic hypertension caused by renal injury: pathophysiology and therapeutic implications. *Clin Exp Nephrol*, 7(3), 167-171 (2003).

41. Evans RG, Gardiner BS, Smith DW, O’Connor PM. Intrarenal oxygenation: unique challenges and the biophysical basis of homeostasis. *American journal of physiology. Renal physiology*, 295(5), F1259-1270 (2008).

42. Nangaku M. Chronic hypoxia and tubulointerstitial injury: a final common pathway to end-stage renal failure. *Journal of the American Society of Nephrology : JASN*, 17(1), 17-25 (2006).

43. Evans RG, Ince C, Joles JA et al. Haemodynamic influences on kidney oxygenation: clinical implications of integrative physiology. *Clinical and experimental pharmacology & physiology*, 40(2), 106-122 (2013).

44. Hansell P, Welch WJ, Blantz RC, Palm F. Determinants of kidney oxygen consumption and their relationship to tissue oxygen tension in diabetes and hypertension. *Clinical and experimental pharmacology & physiology*, 40(2), 123-137 (2013).

45. Singh P, Ricksten SE, Bragadottir G, Redfors B, Nordquist L. Renal oxygenation and haemodynamics in acute kidney injury and chronic kidney disease. *Clin Exp Pharmacol Physiol*, 40(2), 138-147 (2013).
46. Liss P, Cox EF, Eckerbom P, Francis ST. Imaging of intrarenal haemodynamics and oxygen metabolism. *Clin Exp Pharmacol Physiol*, 40(2), 158-167 (2013).

47. Nangaku M, Rosenberger C, Heyman SN, Eckardt KU. Regulation of hypoxia-inducible factor in kidney disease. *Clin Exp Pharmacol Physiol*, 40(2), 148-157 (2013).

48. Kondo N, Kiyomoto H, Yamamoto T et al. Effects of calcium channel blockade on angiotensin II-induced peritubular ischemia in rats. *J Pharmacol Exp Ther*, 316(3), 1047-1052 (2006).

49. Friederich-Persson M, Persson P, Fasching A, Hansell P, Nordquist L, Palm F. Increased kidney metabolism as a pathway to kidney tissue hypoxia and damage: effects of triiodothyronine and dinitrophenol in normoglycemic rats. *Adv Exp Med Biol*, 789, 9-14 (2013).

50. Friederich-Persson M, Thorn E, Hansell P, Nangaku M, Levin M, Palm F. Kidney Hypoxia, Attributable to Increased Oxygen Consumption, Induces Nephropathy Independently of Hyperglycemia and Oxidative Stress. *Hypertension*).

51. Hering D, Zdrojewski Z, Krol E et al. Tonic chemoreflex activation contributes to the elevated muscle sympathetic nerve activity in patients with chronic renal failure. *Journal of hypertension*, 25(1), 157-161 (2007).

52. Marshall JM. Peripheral chemoreceptors and cardiovascular regulation. *Physiological reviews*, 74(3), 543-594 (1994).

53. Blessing WW, Yu Y, Nalivaiko E. Medullary projections of rabbit carotid sinus nerve. *Brain research*, 816(2), 405-410 (1999).

54. Schultz HD, Marcus NJ, Del Rio R. Role of the carotid body in the pathophysiology of heart failure. *Current hypertension reports*, 15(4), 356-362 (2013).

55. Ding Y, Li YL, Schultz HD. Role of blood flow in carotid body chemoreflex function in heart failure. *The Journal of physiology*, 589(Pt 1), 245-258 (2011).

56. Barnett S, Mulligan E, Wagerle LC, Lahiri S. Measurement of carotid body blood flow in cats by use of radioactive microspheres. *Journal of applied physiology*, 65(6), 2484-2489 (1988).

57. Nobrega AC, O'Leary D, Silva BM, Marongiu E, Piepoli MF, Crisafulli A. Neural regulation of cardiovascular response to exercise: role of central command and peripheral afferents. *BioMed research international*, 2014, 478965 (2014).

58. Li J, Xing J. Muscle afferent receptors engaged in augmented sympathetic responsiveness in peripheral artery disease. *Frontiers in physiology*, 3, 247 (2012).

59. Fisher JP, Seifert T, Hartwich D, Young CN, Secher NH, Fadel PJ. Autonomic control of heart rate by metabolically sensitive skeletal muscle afferents in humans. *The Journal of physiology*, 588(Pt 7), 1117-1127 (2010).

60. Li J, Sinoway LI. ATP stimulates chemically sensitive and sensitizes mechanically sensitive afferents. *American journal of physiology. Heart and circulatory physiology*, 283(6), H2636-2643 (2002).

61. Berger A, Grossman E, Katz M et al. Exercise blood pressure and the risk for future hypertension among normotensive middle-aged adults. *Journal of the American Heart Association*, 4(4) (2015).

62. Wang HJ, Li YL, Gao L, Zucker IH, Wang W. Alteration in skeletal muscle afferents in rats with chronic heart failure. *The Journal of physiology*, 588(Pt 24), 5033-5047 (2010).
613 63. Vongpatanasin W, Wang Z, Arbique D et al. Functional sympatholysis is impaired in hypertensive humans. *The Journal of physiology*, 589(Pt 5), 1209-1220 (2011).

614 64. Mortensen SP, Saltin B. Regulation of the skeletal muscle blood flow in humans. *Experimental physiology*, 99(12), 1552-1558 (2014).

615 65. Rosenmeier JB, Hansen J, Gonzalez-Alonso J. Circulating ATP-induced vasodilatation overrides sympathetic vasoconstrictor activity in human skeletal muscle. *The Journal of physiology*, 558(Pt 1), 351-365 (2004).

616 66. Nishiyama A, Fujisawa Y, Fukui T et al. Role of nitric oxide in regional blood flow in angiotensin II-induced hypertensive rats. *Hypertension research: official journal of the Japanese Society of Hypertension*, 24(4), 421-427 (2001).

617 67. Hellsten Y, Nyberg M, Jensen LG, Mortensen SP. Vasodilator interactions in skeletal muscle blood flow regulation. *The Journal of physiology*, 590(Pt 24), 6297-6305 (2012).

618 68. Koba S, Watanabe R, Kano N, Watanabe T. Oxidative stress exaggerates skeletal muscle contraction-evoked reflex sympathoexcitation in rats with hypertension induced by angiotensin II. *American journal of physiology. Heart and circulatory physiology*, 304(1), H142-153 (2013).

619 69. Nishiyama A, Fukui T, Fujisawa Y et al. Systemic and Regional Hemodynamic Responses to Tempol in Angiotensin II-Infused Hypertensive Rats. *Hypertension*, 37(1), 77-83 (2001).

620 70. Zhao W, Swanson SA, Ye J et al. Reactive oxygen species impair sympathetic vasoregulation in skeletal muscle in angiotensin II-dependent hypertension. *Hypertension*, 48(4), 637-643 (2006).

621 71. Pan HL, Deal DD, Xu Z, Chen SR. Differential responses of regional sympathetic activity and blood flow to visceral afferent stimulation. *American journal of physiology. Regulatory, integrative and comparative physiology*, 280(6), R1781-1789 (2001).

622 72. Sartor DM. Sympathoinhibitory signals from the gut and obesity-related hypertension. *Clinical autonomic research: official journal of the Clinical Autonomic Research Society*, 23(1), 33-39 (2013).

623 73. Prewitt RL, Rice DC, Dobrian AD. Adaptation of resistance arteries to increases in pressure. *Microcirculation*, 9(4), 295-304 (2002).

624 74. Reid JL. Vascular reactivity, adrenergic mechanisms, and arteriolar resistance in hypertension. *J Cardiovasc Pharmacol*, 12 Suppl 3, S114-120 (1988).

625 75. Mayhan WG, Werber AH, Heistad DD. Protection of cerebral vessels by sympathetic nerves and vascular hypertrophy. *Circulation*, 75(1 Pt 2), I107-112 (1987).

626 76. Baumbach GL, Heistad DD, Siems JE. Effect of sympathetic nerves on composition and distensibility of cerebral arterioles in rats. *The Journal of physiology*, 416, 123-140 (1989).

627 77. Cates MJ, Steed PW, Abdala AP, Langton PD, Paton JF. Elevated vertebrobasilar artery resistance in neonatal spontaneously hypertensive rats. *Journal of applied physiology*, 111(1), 149-156 (2011).

628 78. Jensen KJ, Alpini G, Glaser S. Hepatic nervous system and neurobiology of the liver. *Comprehensive Physiology*, 3(2), 655-665 (2013).
79. Gao L, Zhu Z, Zucker IH, Wang W. Cardiac sympathetic afferent stimulation impairs baroreflex control of renal sympathetic nerve activity in rats. *American journal of physiology. Heart and circulatory physiology*, 286(5), H1706-1711 (2004).

80. Kennedy C. ATP as a cotransmitter in the autonomic nervous system. *Autonomic neuroscience : basic & clinical*, 191, 2-15 (2015).

81. Gibbs GF, Drummond PD, Finch PM, Phillips JK. Unravelling the pathophysiology of complex regional pain syndrome: focus on sympathetically maintained pain. *Clinical and experimental pharmacology & physiology*, 35(7), 717-724 (2008).

82. Schultz HD, Li YL, Ding Y. Arterial chemoreceptors and sympathetic nerve activity: implications for hypertension and heart failure. *Hypertension*, 50(1), 6-13 (2007).

83. Paton JF, Dickinson CJ, Mitchell G. Harvey Cushing and the regulation of blood pressure in giraffe, rat and man: introducing 'Cushing's mechanism'. *Experimental physiology*, 94(1), 11-17 (2009).

**Outlines the Cushing's mechanism hypothesis.**

84. Dickinson CJ, Thomson AD. A post mortem study of the main cerebral arteries with special reference to their possible role in blood pressure regulation. *Clinical science*, 19, 513-538 (1960).

85. Cates MJ, Dickinson CJ, Hart EC, Paton JF. Neurogenic hypertension and elevated vertebrobasilar arterial resistance: is there a causative link? *Current hypertension reports*, 14(3), 261-269 (2012).

86. Marina N, Ang R, Machhada A et al. Brainstem hypoxia contributes to the development of hypertension in the spontaneously hypertensive rat. *Hypertension*, 65(4), 775-783 (2015).

87. Baguley IJ, Perkes IE, Fernandez-Ortega JF, Rabinstein AA, Dolce G, Hendricks HT. Paroxysmal sympathetic hyperactivity after acquired brain injury: consensus on conceptual definition, nomenclature, and diagnostic criteria. *Journal of neurotrauma*, 31(17), 1515-1520 (2014).

88. Abdulqawi R, Dockry R, Holt K et al. P2X3 receptor antagonist (AF-219) in refractory chronic cough: a randomised, double-blind, placebo-controlled phase 2 study. *Lancet*, 385(9974), 1198-1205 (2015).

89. Nishiyama A, Seth DM, Navar LG. Renal interstitial fluid concentrations of angiotensins I and II in anesthetized rats. *Hypertension*, 39(1), 129-134 (2002).

90. Tanaka T, Nangaku M. Drug discovery for overcoming chronic kidney disease (CKD): prolyl-hydroxylase inhibitors to activate hypoxia-inducible factor (HIF) as a novel therapeutic approach in CKD. *J Pharmacol Sci*, 109(1), 24-31 (2009).

91. Yu X, Fang Y, Liu H et al. The balance of beneficial and deleterious effects of hypoxia-inducible factor activation by prolyl hydroxylase inhibitor in rat remnant kidney depends on the timing of administration. *Nephrol Dial Transplant*, 27(8), 3110-3119 (2012).

**Reference annotation:**

* Of interest

** Of considerable interest
Figure 1. Schematic illustrating the **visceral afferent activation hypothesis of hypertension**.

When afferents become sensitized due to, for example, high sympathetic activity, circulating angiotensin II, atheroma, or congenital predisposition (although exact mediator(s) remain to be identified) they reflexively increase sympathetic vasomotor tone reducing making an organ vulnerable to hypoxic-hypoperfusion and reducing its blood flow reserve/capacity. We propose that this triggers release of metabolites that activate excessive afferent nerve activity, which exacerbate the reflex-evoked sympathetic vasoconstriction. Widespread sympathetic activation may recruit additional afferent systems resulting in additional drivers for maintaining pathologically high levels of sympathetic activity and total peripheral resistance. Thus, the system degenerates into a positive feedback loop in hypoxic-hypoperfusion and reduced blood flow reserve/capacity acts as an amplifier and conceivable initiator of sympathoexcitatory afferent drive. Consequently vasoconstriction, arteriole re-modelling increased total peripheral resistance and end organ damage will amplify the organ blood flow supply-demand mismatch compounding the problem of hypoperfusion and the development and maintenance of hypertension. We do not rule out that excessive sympathetic activity itself sensitises the afferent nerves mediating the reflex-evoked sympatho-excitation. **Artwork** was provided by Michel Cekalovic (www.moviesandgraphics.com).
Disclosure

This work was supported by the British Heart Foundation (No. FS/14/2/30630 and RG/12/6/29670), the Royal Society (RG140387) and the European Union, Seventh Framework Programme, Marie Curie Actions (CARPEDIEM - No 612280).

Dr A Ford is the chief scientific officer for Afferent Pharmaceuticals.
Figure 1

The visceral afferent activation hypothesis of hypertension

- Vasoconstriction
- Arteriole re-modelling
- Total Peripheral Resistance ↑
- End organ damage

- Other organs
- Kidney
- Skeletal Muscle
- Carotid Body

- Organ blood flow supply-demand mismatch
- Afferent activation
- Blood flow reserve/capacity ↓

- Tissue Hypoperfusion

- Sympathetic Efferent ↑

- Brain
  - Cushing Mechanism
  - Congenital Angiotensin-II Sympathetic Humoral

Hypertension