# DRAFT: THE SYMPATHETIC INNERVATION OF THE HEART

Title: The Sympathetic Innervation of the Heart – a Clinical Review

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# INTRODUCTION

The human sympathetic nervous system, the master and commander of the “fight or flight” response, has not adapted adequately to human disease. It is the culprit in multiple pathological states, particularly that of the heart. The sympathetic innervation of the heart is part of the connection between the brain and the heart and it is inherent to physiology and pathophysiology of cardiac autonomic function. The purpose of this review article is to teach clinicians the importance of the sympathetic nervous system in both normal and pathophysiological states, share how pathology stems from inappropriate responses by the autonomic nervous system, and to explore the anatomy and physiology of sympathetic outflow to the heart. The reader should be able to (1) understand the relevant anatomy of the sympathetic nervous system as it innervates the heart, (2) understand the effects of sympathetic tone on the heart, such as chronotropy, inotropy, lusitropy, and dromotropy, and (3) understand how sympathetic dysfunction plays a role in pathological states such as ventricular dysrhythmias, myocardial infarctions, and cardiomyopathies.

# ANATOMIC AND PHYSIOLOGIC CONSIDERATIONS

## Overview

The neural control of the heart is in part a product of its anatomy. The structure, sometimes described as the neurocardiac axis, has three distinct levels: the brain and spinal cord, the thoracic and extracardiac ganglia (EC), and the intrinsic cardiac nervous system (IC).(Ardell & Armour, 2016) These levels send information through afferent and efferent limbs of both the sympathetic and parasympathetic nervous systems, and at each level interactions occur that affect the autonomic state.

[figure: innervation of the heart anatomy]

## Brain and spinal cord level

The spinal cord houses the preganglionic neurons of the SNS within the lateral horns at each vertebral level. Cardiac outflow occurs between the T1 and T6 vertebrae. The neurons exit through the ventral roots that merge into the white rami, which join the sympathetic chain and the ganglia of the EC. In contrast, the vagal preganglionic neurons are in the brain stem, mainly the medullary dorsolateral reticular formation. The thoracic spinal segments have a distinct cardiac rhythm and other frequencies of oscillation that are transmitted to the postganglionic neurons in the heart. The distinct periodicities include 10 Hz, 2-6 Hz, respiratory rates, and slower firing that matches the speed of arterial blood pressure oscillations (Mayer waves).(Malpas, 1998)

Although there is some automaticity of the firing rate of the SNS neurons within the spinal cord, there are many higher orders of influence that affect the activity of the preganglionic cell bodies. For example, nervous activity such as a panic attack, can lead to increased autonomic outflow, but so can events liked traumatic brain injury that leads to hyperactivation and sympathetic storm. Other peripheral and systemic reflexes are also integrated at the level of the spinal cord, such as vasovagal syncope, the mesenteric ganglia response to stress (lumbosacral outflow).

## Thoracic, extracardiac level

The thoracic ganglia that make up the EC contain neurons that directly innervate the myocardium. Both afferent and efferent pathways are present. The most well-studied is of course the stellate ganglia, which carries both preganglionic fibers and postganglionic neurons to the heart. The right stellate ganglia (RSG) and the left stellate ganglia (LSG) are seen to have differences in function based on the location of their nerve endings. Of the ventricles, the RSG is directed towards the anterior and basal aspects, while the LSG is directed towards the posterior and apical aspects. Both ganglia however dually innervate the anterior left ventricular (LV) wall.(Vaseghi et al., 2012) The RSG in particular in addition has predominance in the atria, compared to the LSG. The postganglionic fibers from the thoracic ganglia, as well as the preganglionic fibers from the spinal cord, terminate within a complex neural network of ganglionated plexuses (GPs) within the heart that compose the IC.

## Intrinsic cardiac level

The postganglionic neurons of the IC are found in the GPs, which are the location for the interaction between preganglionic fibers, parasympathetic fibers, and cardiac interneurons. The majority of GPs contain 200-1000 neurons each, and form synapses with sympathetic and parasympathetic fibers that enter the pericardial space.(J. Andrew Armour, Murphy, Yuan, Macdonald, & Hopkins, 1997) The highest density of GPs are near the hilum of the heart, with up to 50% of cardiac ganglia on the dorsal surface of the LA.(Pauza, Skripka, Pauziene, & Stropus, 2000) Sympathetic nerves also travel along the major coronary arteries as a plexus, and decrease in proportion to vessel size to 2 single fibers at level of arterioles.(Dolezel, Gerová, Gero, Sládek, & Vasku, 1978)

The GPs extend epicardially to innervate the atria, interatrial septum, and ventricles, but sympathetic innervation is not uniform. Early studies looked at tyrosine hydroxylase, the enzyme that produces nor epinephrine (NE), to help identify important sympathetic nerves and fibers. The ventricles showed a gradient from base to apex, with the lowest concentration in the apex of the heart.(Pierpont, DeMaster, Reynolds, Pederson, & Cohn, 1985) Another way that the innervation has been studied is by using radiolabeled metaiodobenzylguanidine (MIBG), a catecholamine analog. Studies showed that the inferior wall of the LV had less uptake than the anterior region. (Momose, Tyndale-Hines, Bengel, & Schwaiger, 2001; Morozumi et al., 1997) In contrast, the inferior LV wall has a higher proportion of vagal afferent neurons.(Walker, Thames, Abboud, Mark, & Kloppenstein, 1978)

The layers of the heart also showed differences in sympathetic density. The highest is in the epicardium, and it decreases reaching towards the endocardium. Within the endocardium, there is a right-to-left decreasing gradient of sympathetic innervation, proportional to the density of cholinergic (vagal nerves).(Crick, Anderson, Ho, & Sheppard, 1999) Within the epicardium, there is also ventricle-to-atrium decreasing gradient of innervation. Within the ventricles, sympathetic afferent neurons are the main sensory neurons. They are triggered by predominately chemical stimuli, but also by mechanical stimuli.(J A Armour, Huang, Pelleg, & Sylvén, 1994)

# VENTRICULAR FIBRILLATORY THRESHOLD

Over 100 years ago, John MacWilliam proposed that VF was the mechanism behind SCD, and subsequently Thomas Jonnesco demonstrated that cardiac sympathectomy was protective against ventricular arrhythmias.(de Silva, 1989; Peter J Schwartz, De Ferrari, & Pugliese, 2017) Other corroborative studies by Bernard Lown showed that vagus nerve stimulation decreased the vulnerability of the heart to VF while vagotomy increased it.(Kolman, Verrier, & Lown, 1975; P. J. Schwartz, Verrier, & Lown, 1977) This adequately argues that sympathetic tone is in part culpable for VF/VT events.

[figure of VF threshold and vagotomy]

The unopposed sympathetic nerve is pathologic. Stimulation of the SNS however can occur from higher nervous factors. An excellent example is how the frequency of premature ventricular contractions increased under psychological stress, suggesting that even transient nervous factors lead to electrical instability.(Lown, Verrier, & Rabinowitz, 1977) These extrasystole beats can be reduced by the introduction of beta-adrenergic blockade.(Matta, Lawler, Lown, & Boston, n.d.) Empiric and anecdotal evidence provided the initial insight into how sudden death was triggered by psychological stress. Engel described several categories of traumatic life settings that precipitated sudden death, from the loss of a loved one, acute grief, personal danger, and even triumph. This pattern was found to play out in a larger scale, with case series by Greene and Rahe that demonstrated hundreds of episodes of sudden death preceded acute and chronic emotional events.(Greene, Goldstein, & Moss, 1972; Rahe, Bennett, Romo, Siltanen, & Arthur, 1973)

[figure: PVC frequency increased with stress]

The evolutionary purpose of sympathetic outflow to the heart allows for a by-product, the decrease in the VF threshold that is seen with stellate stimulation . Its physiologic role however is related to the original “fight or flight” response. Studies focused on the stellate ganglia helped to delineate the specific actions the SNS had upon the heart. The basic responses of the heart are inotropy (increased “squeeze”), lusitropy (improved relaxation), chronotropy (increased sinoatrial firing), and dromotropy (improved nerve conduction). There is an element of handed-ness to the innervation, such that the right and left stellate ganglia have differing effects, in part because of location of innervation. The RSG has an higher amount of atrial innervation, including the SA node, and leads to changes in chronotropy. The LSG innervates the ventricles predominantly, leading to an increase in inotropy. The relationship is complex, as right stellectomy can lead to compensatory contralateral activation.(P. J. Schwartz et al., 1977) Bilateral stellectomy though has a well-established effect of increased the resilience of the heart to VT and VF.(Kliks, Burgess, & Abildskov, 1975)

# CORONARY PERFUSION

In an out-of-hospital cardiac arrests, ST-segment elevations after VT or VF event have over a 70% chance of significant coronary artery disease (CAD).(Yannopoulos et al., 2019) Even after an MI, Dr. Bernard Lown noted that patients were at significant risk for SCD and would benefit from a coronary care unit that focused on prophylaxis of arrhythmias. How do acute infarction and chronic ischemia generate malignant rhythms? There are acute responses and delayed reorganization of the SNS that explain these findings.

Knowledge of coronary blood flow regulation is important in understanding the pathogenesis of VT and VF. The most prominent regulators of the coronary arteries is based on pressure changes. High pressure leads to sympathetic inhibition, while low pressures causes increased sympathetic efferent outflow which leads to vasoconstriction.(Drinkhill, Mcmahon, & Hainsworth, 1996; McMahon, Drinkhill, & Hainsworth, 1996) The coronary arteries are innervated by both adrenergic and cholinergic neurons, with an increase in the amount of nerve terminals in the smaller arteries and arterioles.(Lever, Ahmed, & Irvine, 1965) The beta-1 adrenergic receptors (B1AR) predominate the larger conduit arteries while the smaller vessels have a higher proportion of B2AR and alpha-1 adrenergic receptors (A1AR).(Baumgart et al., 1999; Murphree & Saffitz, 1988) For example, in cardiac transplant patients, as they have no connection between the EC and IC, systemic NE leads to coronary vasodilation in the large vessels (e.g. left anterior descending) in proportion to the concentration of sympathetic nerve terminals.(Di Carli et al., 2002) However, in the event of ischemia or increased workflow, coronary vasoconstriction can be attenuated by the metabolic waste productions like adenosine.(Abe, Morgan, & Gutterman, 1997) These differences in proportions of receptors are responsible for balancing perfusion through local vasodilation and vasoconstriction in the healthy heart, as a response to cardiac demand and myocardial contraction. These systems were not built to respond to ischemia.

[figure: coronary perfusion and VF threshold]

The heart responds to acute changes in coronary perfusion with an intense sympathetic response, which subsequently lowers the VF threshold. Transmural infarcts lead to sympathetic denervation, while subendocardial ischemia will likely only impact the vagal afferent nerve endings.(Herre et al., 1988; Zipes, 1990) This was studied by looking at the response of nerves to epicardial stimuli. Non-transmural ischemia still allowed for a response to chemical stimuli, but transmural ischemia lead to apical loss of efferent sympathetic nerves within 20 minutes. (Inoue, Skale, & Zipes, 1988) After 90 minutes, afferent sympathetic and vagal nerves also became denervated.(Barber, Mueller, Davies, Gill, & Zipes, 1985) During these ischemic events, there is an increase in sympathetic excitatory outflow.(Anthony J Minisi & Thames, 1991a).

[figure: zipes myocardial innervation]

However there remains a prolonged risk for arrhythmias after reperfusion. There is differential, heterogenous innervation of sympathetic fibers in the cardiac tissue that become a nidus for arrhythmogenesis. Initially after ischemia, IC neuronal remodeling occurs. There is an immediate and persistent increase in nitric oxide synthase (NOS) containing neurons and a hypersensitivity to NE stimuli leading to generalized excitability.(Hardwick, Ryan, Beaumont, Ardell, & Southerland, 2014) The non-ischemic and ischemic territories develop differential sympathetic efferent activity after events as well.(Neely & Hageman, 1990) Both denervation and hyperinnervation are the response, and at the boundary of preserved and ischemic myocardium there becomes an interdigitation of innervated and denervated tissue.(Huang, Boyle, & Vaseghi, 2017) The nerve-sprouting that occurs is due to an increase in activity of left stellate ganglia in the setting of chronic myocardial ischemia.(Cao et al., 2000; Chen et al., 2001)

Not only does myocardial ischemia and infarction lead to changes in innervation, but also in receptor density and response, which we will discuss in the next section.

# EFFECT OF CATECHOLAMINES

The heart has a unique and appropriate physiologic response to increased demands. In the setting of arousal, either emotional or from environmental triggers, the heart orchestrates a robust response, as it is able to augment its cardiac output two-fold, upwards of 10 L/min. It does this through both system and local responses to catecholamines.

1. Catecholamine-based necrosis
   1. Malignant effects of catecholamines
      1. Takotsubo to discuss apical ballooning
         1. Mortality with Takotsubo is same with traditional ACS
      2. Wellen’s T waves occur in setting of significant apical NE levels
         1. Stress events
         2. Cerebral injury
      3. Effect of adrenergic receptor density on apex of the heart

## Neurotransmitters

* 1. Important neurotransmitters that mediate sympathetic tone
     1. Sympathetic signals
        1. NE
           1. Alpha and beta adrenergic receptors have differential preference of location
        2. Galanin
        3. NPY
     2. Parasympathetic signals
        1. Ach
        2. NOS
     3. TABLE: Describe individual neurohormones and effect on heart

Although NE is the typical mediator of adrenergic fibers, the other relevant neurohormones have an important role in their interactions. Through immunofluorescent staining, multiple neuronal somata have been identified. Choline acetyltransferase (ChAT) produced acetylcholine (ACh), which are typically cardioinhibitory. Cholinergic cell bodies predominate cardiac nerves, making anywhere from 60% to 100% of cardiac ganglia. ChAT somata are also more common in the atria than the rest of the heart. In the presence of NE, the inhibitory effects of ACh are exaggerated in a phenomenon called accentuated antagonism.(Levy, 1971; Stramba-Badiale et al., 1991) Nitric oxide synthase (NOS) produces nitric oxide (NO), and colocalizes with ChAT somata. Its present equally from endocardium to epicardium, but the density favors the base versus the apex.(Brack, Patel, Coote, & Ng, 2007) As it is also a co-transmitter that modulates the vagal effect of increasing the VF threshold, through modifying action potential duration (APD). Vasoactive intestinal peptide (VIP) is also co-released with ACh, however neuronal somata containing VIP are scarce within the IC. All of the nerve fibers reaching into the cardiac ganglia however are reactive for VIP which likely comes from central sources.(Hoover et al., 2009; Parsons, Locknar, Young, Hoard, & Hoover, 2006)

TH is responsible for NE production, but surprisingly 10-20% of all neurons contain both TH and ChAT.(Pauza et al., 2013) Both the left and right coronary plexuses however are mainly adrenergic.(Pauziene et al., 2016) Alongside NE, neuropeptide Y (NPY) is co-released. At the level of the synapse, NPY attenuates the effect of vagal tone by decreasing ACh release.(Herring, Lokale, Danson, Heaton, & Paterson, 2008) It also functions as a potent coronary vasoconstrictor acutely, however may lead to angiogenesis in the long-term.(Herring, 2015) NPY, in human studies, leads to mild constriction of epicardial arteries for all patients. However, in those with microvascular angina, defined by normal left heart catherization but abnormal myocardial perfusion, NPY leads to transient myocardial ischemia.(Rosano et al., 2017) Galanin is also released alongside NPY, and it acts by inhibiting cholinergic nerves to reduce ACh release. Galanin receptors (GalR1) are found on ChAT somata and synapses, and may mediate the breaking of vagal bradycardia as it is expressed strongly at the sinoatrial (SA) node.(Herring et al., 2012) Galanin is normally only co-expressed in ~5% of TH somata in the stellate, however after injury, its levels are increased to almost all neurons within 72 hours.(Herring et al., 2012)

The direct effect of sympathetic firing is through the release of NE, which can bind to four different adrenergic receptors (AR). B1 and B2 adrenergic recept

* + 1. B1 and B2 adrenergic receptors are present in cardiac myocytes at sympathetic synaptic terminals; B1AR accumulate at synapses, while B2AR undergo endocytosis/internalization. (Shcherbakova et al., 2007) Beta-agonists lead to increase in cardiac mass through increased size of cardiac myocytes. (Franzoso, Zaglia, & Mongillo, 2016; Zaglia et al., 2013)
    2. Almost all cardiomyocytes are in contact with sympathetic neurons (similar proportion to contact c- capillaries). (Hirsch et al., 2013) Basal/trophic sympathetic release leads to cardiomyocyte eutrophy (loss of beta-agonism leads to atrophy).

## Cardiomyopathy

1. Increased sympathetic tone in ischemic HF models (porcine) improves myocardial contraction, decreased oxygen consumption, decreases intraventricular desynchrony, all without elevation of NE. (Liu et al., 2012)
2. After developing late-stage HF, neuronal bodies become hypertrophied and edematous. They become less excitable and may lead to vagal withdrawal. (Singh et al., 2013)
3. In both ischemic and dilated CM…B1 receptor downregulation (proportion of subtypes are the same compared to healthy). Transmural distribution is different, c- lower B1 receptors found in subendocardium. (Beau, Tolley, & Saffitz, 1993)
4. Cardiac sympathetic afferent reflex (CSAR) causes minimal increase in contractility, but has increased peripheral vasoconstriction (compared to rat controls). CSAR can be inhibited by epicardial lidocaine – decreased contractility more in HF rats than control (also caused drop in LVEDP paradoxically). (Wang, Rozanski, & Zucker, 2017)
   1. Myocardial contractility
      1. NE release by the heavily sympathetically-innervated myocardium leads to Ca++ channel activity and ryanodine receptor (RyR), which leads to increased cytosolic Ca++. Effect is increased inotropy/lusitropy. (Shan et al., 2010) Sympathetic stimuli with NE at SA node also leads to increased myocardial interstitial levels of NE, which lead to ventricular inotropy.
5. Electrical conduction
   * 1. Chronotropy/dromotropy
        1. SA node firing rate depends on “funny current”, which has inward-rectifying Na+ current that leads to depolarization through the hyperpolarization-activated cyclic nucleotide-gated channel (HCN). Sympathetic tone leads to dromotropy/chronotropy through increased HCN activity, spontaneous SA depolarization rate, and sarcoplasmic reticulum release of Ca++, as well increased depolarization through other neuronal bundles (e.g. His bundle, AV node, etc). (Franzoso et al., 2016; Liao, Lockhead, Larson, & Proenza, 2010)
     2. Repolarization
        1. Effective refractory period (ERP) are shorted by sympathetic excitation, while sympathetic inhibition prolongs ERP… similar in endocardium/epicardium. (Martins & Zipes, 1980) Transmural dispersion of repolarization also shortened by sympathetic activity, prolonged by beta-blockade. (Dukes & Vaughan Williams, 1984)

# CONCLUSION

* Review objectives
* Summary statement

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