In 1664, the first anatomically correct depiction of the sympathetic nervous system came from Thomas Willis and his circle of London anatomists,1 included in The Anatomy of the Brain and Nerves, 1664 (Figure 1). This, the first work dedicated completely to the nervous system, also described the arterial loops at the base of the brain, which we now know as the Circle of Willis.1 Christopher Wren, an anatomist member of the group, was the principal illustrator before being asked by the City Fathers to turn his talents to town planning, architecture, and cathedral building after the 1666 Great Fire of London.

Almost 2 centuries later, subsequent microscopic examination demonstrated that blood vessel walls were densely innervated, leading Stelling in 18402 to correctly conclude that these vasomotor fibers were in fact sympathetic nerves that were carried from the central nervous system to the blood vessels. In the mid-19th century, celebrated European physiologists, including Brown-Sequard, Waller, and Bernard,2 built on these observations, demonstrating vasoconstriction with electrical stimulation of the cut nerves and vasodilatation on nerve section, which indicated that the sympathetic fibers exerted a tonic, vasoconstrictor influence. The pressor nerves had gained recognition.

Identification of the sympathetic neurotransmitter proved to be difficult. Claims for epinephrine3,4 and the hypotheticalexitants I and E confused the picture. Ulf von Euler compared bioassay responses of epinephrine, norepinephrine, and dihydroxy norephedrine with those of cattle splenic nerve extract, by testing blood pressure (BP) responses in the anesthetized cat and contractile responses in the isolated pregnant rabbit uterus, to definitively demonstrate the primary transmitter to be norepinephrine.5 This discovery provided the theoretical knowledge for the development of pharmacological antagonists of the sympathetic nervous system, subsequently used as antihypertensive drugs, and quickly led to the application of neurochemical methods, initially the measurement of norepinephrine excretion in urine,6 in efforts to quantify sympathetic nervous system activity in humans.

The publication of the first sensitive and specific plasma catecholamine assay by Engelman et al7 was a milestone in the field. For a time, plasma norepinephrine measurements were the principal method for the investigation of sympathetic neural mechanisms in clinical medicine. Plasma norepinephrine measurements, although providing a useful guide to sympathetic nervous system function, have substantial limitations. The principal one was that this or in fact any other global index of sympathetic nervous function provides no information on the regional patterning of sympathetic nervous responses. This runs contrary to the observation of the sympathetic nervous system in which sympathetic nervous responses are regionally differentiated. Precise quantification of individual regional sympathetic nervous outflows was needed. This need came to be met by the sympathetic nerve recording technique of clinical microneurography and by radiotracer-derived measurements of regional norepinephrine spillover to plasma.

**Microneurography**

Hagbarth and Vallbo,8 while studying sensory nerves in humans, noted interfering neural discharges which after comprehensive investigation they identified as originating from postganglionic sympathetic nerves. They elaborated this observation into a clinical method for measuring sympathetic nerve efferent multifiber traffic. This technique of clinical microneurography, initially explored and popularized by Wallin et al,9 provided a method for studying nerve firing in subcutaneous sympathetic outflows distributed to skin and the skeletal muscle vasculature. The technique involves insertion of a fine tungsten electrode through the skin, with positioning of the electrode tip in sympathetic fibers of, most commonly, the common peroneal nerve near the head of the fibula. Multifiber recordings of bursts of nerve activity, synchronous with the heart beat, are generated in skeletal muscle vascular efferents.9 Single-fiber sympathetic recording has also been successfully performed in humans.10,11

**Contemporary Methods for Studying the Regional Sympathetic Nervous System Activity in Humans**

The 2013 American Heart Association High Blood Pressure Research Council Excellence Award in Hypertension Research Plenary Lecture, “The Sympathetic Nervous System Moves Toward Center Stage in Cardiovascular Medicine: From Thomas Willis to Resistant Hypertension” was presented by the author at the Annual Scientific Sessions of the Council in New Orleans, LA on September 13, 2013.

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Regional Norepinephrine Spillover Measurements

A special impetus to the development of techniques for studying the rates of overflow of norepinephrine to the circulation was provided by the lack of clinical methods for studying human sympathetic nervous outflow to otherwise inaccessible organs, such as the heart and kidneys. The inapplicability of the neural recording methodology for clinical research on internal organs led to a continuing search for alternative techniques, especially biochemical ones.

For these reasons, I established techniques for measuring organ-specific norepinephrine release to plasma for studying regional sympathetic nervous function in humans, which I will now describe in some detail. The relationship that, in general, holds between the sympathetic nerve firing rate of an organ and the rate of spillover of norepinephrine into its venous effluent provides the experimental justification for using measures of regional norepinephrine release as a clinical index of sympathetic nervous tone in individual organs.

During constant rate intravenous infusion of tritiated norepinephrine, outward flux of endogenous norepinephrine from an organ (regional norepinephrine spillover) can be measured by isotope dilution:

\[ \text{Regional norepinephrine spillover} = \left[ \left( C_V - C_A \right) + C_A E \right] \times \text{PF}, \]

where \( C_V \) and \( C_A \) are the plasma concentrations of norepinephrine in regional venous and arterial plasma, \( E \) is the fractional extraction of tritiated norepinephrine in transit of blood through the organ, and \( \text{PF} \) is the organ plasma flow. The theory of this was clear enough, but the implementation was complicated, specifically how could the central venous catheterization necessary for sampling from the veins draining internal organs receive ethics committee approval? The solution lay in adding the research study to clinically justified procedures. Sampling from the renal vein for renin measurements was performed for the evaluation of hypertension at the time to screen for a functionally significant renal artery stenosis. This provided an opportunity, with appropriate consent, to establish

the renal norepinephrine spillover measurement methodology. In patients with heart failure, central venous catheterization was also common to measure pulmonary artery wedge pressure; this enabled the coronary sinus venous sampling required for cardiac norepinephrine spillover measurements.

Of all measurements of regional norepinephrine spillover, it was those in the heart and the kidneys that have had most direct clinical relevance. Measurements of cardiac norepinephrine spillover in heart failure documented activation of the cardiac sympathetic outflow in patients with heart failure, providing key theoretical background for the testing and introduction of \( \beta \)-adrenergic blockers as therapy. Measurements of renal norepinephrine spillover in essential hypertension documented preferential activation of the renal sympathetic outflow, key to the development of catheter-based renal denervation as therapy for drug-resistant hypertension. The measurement of cardiac norepinephrine spillover in a patient with heart failure did provide a Eureka moment in 1982, with detection of an inexplicably high value. This was surprising because the content of norepinephrine in the failing human myocardium is markedly reduced, and the failing heart at that time being thought to be sympathetically denervated. This finding in a single patient was reinforced by further studies, with publication of the finding 4 years later, establishing that in reality the cardiac sympathetic outflow in heart failure is activated at a high level.

Human Neural Cardiovascular Pathophysiology: Translation to Patient Care

This review provides evidence that abnormalities of the sympathetic nervous system are commonly crucial in the development and clinical expression of cardiovascular disorders. Examples include congestive heart failure, the disorders of postural circulatory control causing orthostatic syncope and essential hypertension. These abnormalities involve ongoing activation of the sympathetic outflows to the heart and kidneys in hypertension and heart failure and impaired postural sympathetic circulatory responses in orthostatic intolerance disorders.

The translation of knowledge of pathophysiology such as this into better medical care for patients is an important goal for clinical scientists. The achievement of this transition, from mechanisms to medical management, is at differing stages of development with the different conditions. With cardiac failure, clinical translation is mature, knowledge of cardiac neural pathophysiology having led to the introduction of \( \beta \)-adrenergic blockers. With essential hypertension, translation has emerged in the application of catheter-based renal sympathetic nerve ablation for treatment of patients with severe drug-resistant essential hypertension resistant to pharmacological treatment. With postural syncope syndromes, knowledge of the neural pathophysiology is preliminary only, and any clinical translation remains for the future.

Cardiac Failure

There were 3 important historical antecedents to contemporary knowledge of sympathetic nervous pathophysiology in heart failure. The first was the observation that the concentration of the sympathetic nervous neurotransmitter, norepinephrine,
Concentration, with diminished survival being present in those
failure is related to their venous plasma norepinephrine concent-
with diminished survival being present in those
with the highest norepinephrine concentrations. But these
crucial observations left a paradox: why is clinical outcome in
heart failure related to sympathetic activation when the heart,
through its sympathetic denervation, should be protected?

It was research by Bristow et al9 that challenged these
concepts, causing a paradigm shift in the conceptualization of
the neural pathophysiology of heart failure—the finding
of a selective reduction in β1-adrenoceptors in failing human
myocardium, these receptors being in close proximity to sym-
pathetic nerve varicosities. In contrast, normal extrajunctional
β2-adrenoceptor numbers suggested to these investigators9
that the sympathetic nerves of the failing heart must, in fact,
be intact and actually release norepinephrine at an increased
rate. The expected finding in sympathetic denervation of
β1-adrenoceptor upregulation definitely was absent.

When my laboratory applied organ-specific tracer kinetic
techniques using radiolabeled norepinephrine, this hypothesis
was confirmed with demonstration that the sympathetic ner-
vous outflow to the heart is actually preferentially stimulated
in severe congestive cardiac failure (emphatically, the failing
heart is not sympathetically denervated).17,21,27 Rates of norepi-
nephine spillover from the failing human heart to plasma are
sustained at ≈50× normal in untreated patients,17,21,27 approxi-
mately equal to the rate of norepinephrine release observed
transiently in the healthy heart during near-maximal exercise.
Furthermore, a strong link was demonstrated between the level
of cardiac sympathetic nervous stimulation in heart failure and
the development of ventricular arrhythmias, progressive left
ventricular deterioration, and reduced survival.22,45

Informed with this knowledge, Packer et al40 devised and
conducted the first definitive β-adrenergic blocker trial for
congestive heart failure, the Carvedilol trial. This trial estab-
lished that chronic β-adrenergic blockade in cardiac failure
could be life-saving.

Postural Circulatory Dysregulation and Syncope
Orthostatic intolerance is the descriptive umbrella term for a
heterogeneous group of disorders characterized by recurrent
postural syncope. The syncope is a transient loss of conscious-
ness and postural tone developing secondary to a fall in cere-
bral perfusion, this cerebral perfusion fall being commonly
caused by a precipitous drop in BP. In health, standing leads
to ≈700 mL of the circulating blood volume being displaced
into capacitance vessels of the lower limbs and pelvis.44 This
sequestration of blood results in the activation of compensa-
tory neural reflexes. The sympathetic nervous system provides
the pivotal reflex neurocirculatory adjustments that stabilize
BP during standing.44

The origins of recurrent postural syncope, no doubt diverse,
remain rather obscure, despite extensive investigation. In
clinical practice, 2 broad clinical phenotypes of recurrent
postural syncope are identified, either with or without neural
degeneration45,46:

1. Neurodegenerative disorders causing postural hypotensi-
on: Patients with sympathetic nerve degeneration (pure
autonomic failure), degeneration of brain regions regu-
lating the circulation (multiple system atrophy), and the
Parkinson disease (where both mechanisms may apply)
often experience disabling postural hypotension and syn-
cope, commonly so severe that prolonged standing and
walking are impossible. Diagnostic distinction between
these conditions is difficult but is important, as prognosis
differs (pure autonomic failure typically is stable for
decades, whereas multiple system atrophy inevitably
progresses to multisystem involvement and death), as do
treatment responses.45,46

2. Syndromes of autonomic circulatory dysregulation:
More common than the neurodegenerative autonomic
illnesses, and described here are impairments of func-
tional sympathetic circulatory responses to the gravity
challenge imposed by standing.

Postural Tachycardia Syndrome
This syndrome is typified by an exaggerated reflex sympathetic
nervous system response to standing, apparently underlying the
tachycardia.32,34,35,45,46 Neurally mediated cerebral vascon-
striction with reduction of cerebral blood flow seems to be
common and is the cause of syncope.47 Postural hypotension
is usually absent. The research of my group implicates aug-
mentation of the postural sympathetic neural signal as a result
of severe deficiency of the noradrenaline transporter protein45
as a mechanism of the postural tachycardia and excessive pos-
tural fall in cerebral blood flow. The human cerebral blood
vessels do have a functional sympathetic innervation.15

Recurrent Vasovagal (Neurocardiogenic) Syncope
Recurrent postural fainting can occur in apparently healthy
people. There are 2 variants: the first of these being patients
with low supine BP, individuals whose supine systolic BP is at
the extreme lower end of the normal range, 75 to 90 mm Hg.
In my clinical practice, I find this to be a common form of
recurrent postural vasovagal syncope.38 These patients com-
monly present at postural syncope clinics, but their low supine
BP is often discounted as a basis for the syncope, although
previously identified as deleterious in the medical literature.45
These patients are commonly informed that low BP is actu-
ally healthy, protecting against the development of strokes
and myocardial infarction. The second recurrent vasovagal
syncope variant involves patients with recurrent syncope and
normal supine BP. This is the commonest and most perplexing
clinical variant. Clinical examination discloses no abnormali-
ties. The primary pathophysiology of this disorder remains
unknown, and treatment is usually ineffective.

The knowledge base for precise diagnosis and treatment
of the postural circulatory control disorders has until recently
remained dismally deficient.45,46 My group has recently made
some progress in delineating the neural circulatory patho-
physiology of recurrent postural vasovagal syncope, with the
Sympathetic nervous responses to head-up tilting in healthy controls (n=18) and patients with the low supine systolic BP fainting phenotype (LSSBP; n=15) and normal supine systolic BP phenotype (NSSBP; n=18) are compared. A. Measurement of sympathetic nerve activity during graded head-up tilt in healthy people and in patients with recurrent postural syncope. The graph depicts a paradoxically higher nerve firing rates in the LSSBP patients with the low BP phenotype, despite their low BP, than in healthy controls and subjects with the normal supine BP phenotype (Figure 2).

B. Norepinephrine release to plasma during graded head-up tilt. Norepinephrine spillover was markedly reduced (P<0.01) in the LSSBP patients with the low BP phenotype, compared to that seen in patients with genetic dopamine-β-hydroxylase deficiency, who have low rates of NE synthesis and release, high rates of sympathetic nerve firing, and postural syncope. In contrast, sympathetic nerve protein analysis in the normal supine systolic BP postural syncope phenotype indicated that TH is normal, but norepinephrine transporter protein, which terminates the neural signal, is elevated. Increase in norepinephrine transporter protein could, perhaps, explain the low NE spillover to plasma from the synapse we find and the propensity to faint by prematurely clearing NE from the synaptic cleft, minimizing cardiovascular adrenoceptor stimulation.

To summarize, recurrent vasovagal syncope in the low and normal systolic BP phenotypes is characterized by an impaired neurovascular response to standing, apparently taking the form of an electrochemical disconnect in sympathetic nerves, with normal nerve firing being accompanied by markedly reduced neurotransmitter spillover. In planned research, the norepinephrine prodrug dihydroxyphenylserine, which is converted to norepinephrine within sympathetic nerves by dihydroxyphenylserine-decarboxylase, is to be administered to vasovagal patients with the low supine systolic BP phenotype.
The syndrome of neurogenic essential hypertension accounts for no <50% of all cases of high BP. This estimate is based on both the proportion of untreated patients with essential hypertension who have demonstrable sympathetic excitation and the number in whom substantial BP lowering is achieved, and the extent of this lowering, with antiadrenergic drugs. In a truly international endeavor from many research groups, the application of sympathetic nerve recording and norepinephrine spillover methodologies has identified activated sympathetic outflow to the skeletal muscle vasculature and kidneys. Sympathetic nervous system activation is evident in both lean and obese patients with hypertension, sympathetic activation demonstrable with microneurography is particularly prominent in the metabolic syndrome and obesity-related hypertension. In the heightened sympathetic activation seen when hypertension is accompanied by obesity, hyperinsulinemia, hyperleptinemia, and obstructive sleep apnea have all been invoked as prime movers, but in reality the precise mechanism remains uncertain.

Does this sympathetic activation initiate and maintain the BP elevation as has been suggested? There is strong evidence to support this claim. In patients with resistant hypertension, responding inadequately to concurrent treatment with multiple antihypertensive drug classes, including angiotensin-converting enzyme inhibitors, angiotensin receptor blockers, dihydropyridine calcium channel blockers, and diuretics, catheter-based radiofrequency ablation of the renal sympathetic nerves targeting the activation of the renal sympathetic outflow lowers BP remarkably.

And this sympathetic nervous activation present in essential hypertension has microcirculatory effects beyond BP elevation, causing the insulin resistance central to the commonly comorbid metabolic syndrome. Renal denervation, through the central sympathetic inhibition it causes by the ablation of renal afferent nerves, breaks this link, reducing insulin resistance.

**Renal Denervation for Drug-Resistant Hypertension: Observations of a Founder**

The sympathetic nervous system is the forgotten pathway in the treatment of hypertension. Despite the importance of neural pathophysiological mechanisms in pathogenesis, therapy specifically targeting the sympathetic nervous system is currently underused. This has changed with the testing of device-based therapies for reducing sympathetic nervous system activity and consequently BP.

In earlier times, before the availability of antihypertensive drugs, extensive surgical sympathectomy was used as a treatment for severe hypertension; survival benefit was demonstrated, but complication rates were high as was morbidity from the extensive denervation, which did not specifically target the kidneys. In that era, there was no theory that the renal nerves were a prime mover in hypertension pathogenesis. In many experimental models of hypertension, the sympathetic outflow to the kidneys is activated, and renal sympathectomy typically prevents the development of the hypertension.

In elegant studies in rodents, the renal nerves have been demonstrated to stimulate secretion of renin from the juxtaglomerular apparatus to promote renal tubular reabsorption of sodium and to cause renal vasoconstriction, reducing
Renal Denervation for Resistant Hypertension: the End of the Beginning

The first catheter-based renal denervation procedure for drug-resistant hypertension was performed on June 6, 2007. More than 6 years later, there remain many unanswered questions. To paraphrase the memorable wartime quote of Winston Churchill (November 1942), out of context, “this is, perhaps, the end of the beginning.” Many questions remain. Will the BP lowering be permanent (or will it be canceled out by renal sympathetic nerve regrowth)? How can patient selection for the renal denervation procedure be optimized, given that pressure reduction is not achieved in all patients? Will BP lowering with renal denervation reduce the rate of clinical cardiovascular end points? Will long-term safety be acceptable? Can milder hypertension be cured? And there are unresolved procedural and technical questions: how much renal denervation is optimal? Is unilateral denervation, now commonly used, beneficial? Will renal denervation show a class effect, with the different energy forms now used in newer denervation devices being equally effective with radiofrequency energy in lowering pressure? I hope the second 6 years of catheter-based renal denervation will answer these questions.

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From Thomas Willis to Resistant Hypertension  
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