US009114262B2

(12) **United States Patent**
Libbus et al.

(10) **Patent No.: US 9,114,262 B2**
(45) **Date of Patent: *Aug. 25, 2015**

(54) **IMPLANTABLE DEVICE FOR EVALUATING AUTONOMIC CARDIOVASCULAR DRIVE IN A PATIENT SUFFERING FROM CHRONIC CARDIAC DYSFUNCTION**

(71) Applicant: **CYBERONICS, INC.**, Houston, TX (US)

(72) Inventors: **Imad Libbus**, St. Paul, MN (US); **Badri Amurthur**, Los Gatos, CA (US); **Bruce H. KenKnight**, Maple Grove, MN (US)

(73) Assignee: **CYBERONICS, INC.**, Houston, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **14/540,337**

(22) Filed: **Nov. 13, 2014**

(65) **Prior Publication Data**

US 2015/0073512 A1 Mar. 12, 2015

Related U.S. Application Data

(63) Continuation of application No. 13/314,133, filed on Dec. 7, 2011, now Pat. No. 8,918,190.

(51) **Int. Cl.**
A61N 1/05 (2006.01)
A61N 1/36 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***A61N 1/36167*** (2013.01); ***A61B 5/02*** (2013.01); ***A61B 5/4836*** (2013.01); ***A61N 1/0551*** (2013.01); ***A61N 1/36053*** (2013.01); ***A61N 1/36114*** (2013.01); ***A61N 1/36139*** (2013.01)

(58) **Field of Classification Search**
CPC ... A61N 1/36; A61N 1/3605; A61N 1/36053; A61N 1/36167; A61N 1/0551; A61N 1/36114; A61N 1/36139
USPC 607/17, 40, 116, 118
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,330,507 A 7/1994 Schwartz
5,522,854 A 6/1996 Ideker et al.
(Continued)

OTHER PUBLICATIONS

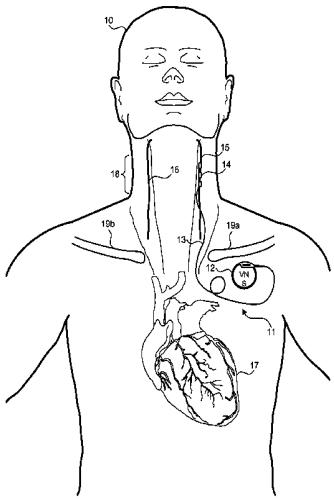
Li, Meihua, et al. "Vagal Nerve Stimulation Markedly Improves Long-Term Surival After Chronic Heart Failure in Rats." Dec. 8, 2003. Amercian Heart Association. vol. 109. pp. 120-124.*
(Continued)

Primary Examiner — Christopher D Koharski
Assistant Examiner — Michael Carey

(57) **ABSTRACT**

An implantable device (**11**) for evaluating autonomic cardiovascular drive in a patient (**10**) suffering from chronic cardiac dysfunction is provided. A stimulation therapy lead (**13**) includes helical electrodes (**14**) configured to conform to an outer diameter of a cervical vagus nerve sheath, and a set of connector pins (**28**) electrically connected to the helical electrodes (**14**). A neurostimulator (**12**) includes an electrical receptacle (**25**) into which the connector pins (**28**) are securely and electrically coupled. The neurostimulator (**12**) also includes a pulse generator configured to therapeutically stimulate the vagus nerve through the helical electrodes (**14**) in alternating cycles of stimuli application and stimuli inhibition (**90**) that are tuned to both efferently activate the heart's intrinsic nervous system and afferently activate the patient's central reflexes by triggering bi-directional action potentials. The neurostimulator (**12**) includes a recordable memory (**29**) storing a baseline heart rate.

13 Claims, 4 Drawing Sheets



(51) **Int. Cl.**

A61B 5/02	(2006.01)
A61B 5/00	(2006.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,707,400	A *	1/1998	Terry et al.	607/44
5,928,272	A	7/1999	Adkins et al.	
5,978,709	A	11/1999	Begemann et al.	
6,006,134	A	12/1999	Hill et al.	
6,266,564	B1	7/2001	Hill et al.	
6,354,991	B1	3/2002	Gross et al.	
6,449,507	B1	9/2002	Hill et al.	
6,473,644	B1	10/2002	Terry, Jr. et al.	
6,508,771	B1	1/2003	Padmanabhan et al.	
6,522,926	B1	2/2003	Kieval et al.	
6,600,954	B2	7/2003	Cohen et al.	
6,610,713	B2	8/2003	Tracey	
6,616,624	B1	9/2003	Kieval	
6,622,041	B2	9/2003	Terry, Jr. et al.	
6,652,449	B1	11/2003	Gross et al.	
6,684,105	B2	1/2004	Cohen et al.	
6,690,971	B2	2/2004	Schauerte et al.	
6,712,772	B2	3/2004	Cohen et al.	
6,718,208	B2	4/2004	Hill et al.	
6,838,471	B2	1/2005	Tracey	
6,839,594	B2	1/2005	Cohen et al.	
6,850,801	B2	2/2005	Kieval et al.	
6,862,480	B2	3/2005	Cohen et al.	
6,892,098	B2	5/2005	Ayal et al.	
6,896,651	B2	5/2005	Gross et al.	
6,904,318	B2	6/2005	Hill et al.	
6,907,295	B2	6/2005	Gross et al.	
6,963,773	B2	11/2005	Borschowa et al.	
6,963,779	B1	11/2005	Shankar	
6,985,774	B2	1/2006	Kieval et al.	
7,010,345	B2	3/2006	Hill et al.	
7,072,720	B2	7/2006	Puskas	
7,123,961	B1	10/2006	Kroll et al.	
7,139,607	B1	11/2006	Shelchuk	
7,158,832	B2	1/2007	Kieval et al.	
7,184,828	B2	2/2007	Hill et al.	
7,184,829	B2	2/2007	Hill et al.	
7,218,964	B2	5/2007	Hill et al.	
7,221,979	B2	5/2007	Zhou et al.	
7,225,017	B1	5/2007	Shelchuk	
7,225,019	B2	5/2007	Jahns et al.	
7,237,320	B2	7/2007	Lam	
7,245,967	B1	7/2007	Shelchuk	
7,260,431	B2	8/2007	Libbus et al.	
7,269,457	B2	9/2007	Shafer et al.	
7,277,761	B2	10/2007	Shelchuk	
7,295,881	B2	11/2007	Cohen et al.	
7,305,265	B2	12/2007	Fukui	
7,321,793	B2	1/2008	Ben Ezra et al.	
7,324,853	B2	1/2008	Ayal et al.	
7,336,997	B2	2/2008	Fukui	
7,346,398	B2	3/2008	Gross et al.	
7,387,603	B2	6/2008	Gross et al.	
7,389,149	B2	6/2008	Rossing et al.	
7,395,119	B2	7/2008	Hagen et al.	
7,403,819	B1	7/2008	Shelchuk et al.	
7,418,292	B2	8/2008	Shafer	
7,452,800	B2	11/2008	Sosnowchik et al.	
7,480,532	B2	1/2009	Kieval et al.	
7,481,759	B2	1/2009	Whitehurst et al.	
7,485,104	B2	2/2009	Kieval	
7,493,167	B2	2/2009	Hussein et al.	
7,499,742	B2	3/2009	Bolea et al.	
7,499,747	B2	3/2009	Kieval et al.	
7,499,748	B2	3/2009	Moffitt et al.	
7,502,650	B2	3/2009	Kieval	
7,542,800	B2	6/2009	Libbus et al.	
7,548,780	B2	6/2009	Libbus et al.	
7,551,958	B2	6/2009	Libbus et al.	
7,561,922	B2	7/2009	Cohen et al.	
7,561,923	B2	7/2009	Libbus et al.	
7,570,999	B2	8/2009	Libbus et al.	
7,582,053	B2	9/2009	Gross et al.	
7,584,004	B2	9/2009	Caparso et al.	
7,587,238	B2	9/2009	Moffitt et al.	
7,606,622	B2	10/2009	Reeve	
7,613,511	B2	11/2009	Wu et al.	
7,613,516	B2	11/2009	Cohen et al.	
7,616,990	B2	11/2009	Chavan et al.	
7,617,003	B2	11/2009	Caparso et al.	
7,623,926	B2	11/2009	Rossing et al.	
7,627,384	B2	12/2009	Ayal et al.	
7,628,750	B2	12/2009	Cohen et al.	
7,630,760	B2	12/2009	Libbus et al.	
7,634,315	B2	12/2009	Cholette	
7,634,317	B2 *	12/2009	Ben-David et al.	607/14
7,640,057	B2	12/2009	Libbus et al.	
7,647,101	B2	1/2010	Libbus et al.	
7,647,114	B2	1/2010	Libbus	
7,650,190	B2	1/2010	Zhou et al.	
7,657,312	B2	2/2010	Pastore	
7,660,628	B2	2/2010	Libbus et al.	
7,664,548	B2	2/2010	Amurthur et al.	
7,668,602	B2	2/2010	Ben-David et al.	
7,672,733	B2	3/2010	Zhou et al.	
7,676,275	B1	3/2010	Farazi et al.	
7,684,866	B2	3/2010	Fowler et al.	
7,689,286	B2	3/2010	Pastore et al.	
7,711,415	B1	5/2010	Farazi et al.	
7,711,421	B2	5/2010	Shafer et al.	
7,734,355	B2	6/2010	Cohen et al.	
7,751,884	B2	7/2010	Ternes et al.	
7,769,442	B2	8/2010	Shafer	
7,769,446	B2	8/2010	Moffitt et al.	
7,778,702	B2	8/2010	Ben-David et al.	
7,778,703	B2	8/2010	Gross et al.	
7,778,711	B2	8/2010	Ben-David et al.	
7,783,353	B2	8/2010	Libbus et al.	
7,797,041	B2	9/2010	Libbus et al.	
7,801,603	B2	9/2010	Westlund et al.	
7,801,604	B2	9/2010	Brockway et al.	
7,801,614	B2	9/2010	Rossing et al.	
7,805,193	B2	9/2010	Libbus et al.	
7,805,203	B2	9/2010	Ben-David	
7,813,805	B1	10/2010	Farazi	
7,813,812	B2	10/2010	Kieval et al.	
7,835,797	B2	11/2010	Rossing et al.	
7,840,266	B2	11/2010	Libbus et al.	
7,840,271	B2	11/2010	Kieval et al.	
7,844,346	B2	11/2010	Cohen et al.	
7,848,812	B2	12/2010	Crowley et al.	
7,848,816	B1	12/2010	Wenzel et al.	
7,869,869	B1	1/2011	Farazi	
7,885,709	B2	2/2011	Ben-David	
7,885,711	B2	2/2011	Ben-Ezra et al.	
7,890,185	B2	2/2011	Cohen et al.	
7,894,907	B2	2/2011	Cowan et al.	
7,904,151	B2	3/2011	Ben-David	
7,904,175	B2	3/2011	Scott et al.	
7,904,176	B2	3/2011	Ben-Ezra et al.	
7,908,008	B2	3/2011	Ben-David et al.	
7,916,013	B2	3/2011	Stevenson	
7,925,342	B2	4/2011	Amurthur et al.	
7,925,352	B2	4/2011	Stack et al.	
7,974,693	B2	7/2011	Ben-David et al.	
8,005,542	B2	8/2011	Ben-Ezra et al.	
8,005,545	B2	8/2011	Ben-David et al.	
8,036,745	B2	10/2011	Ben-David et al.	
8,060,197	B2	11/2011	Ben-David et al.	
8,065,021	B2	11/2011	Gross et al.	
8,083,663	B2	12/2011	Gross et al.	
8,116,881	B2	2/2012	Cohen et al.	
8,131,362	B2	3/2012	Moffitt et al.	
8,160,701	B2	4/2012	Zhao et al.	
8,160,705	B2	4/2012	Stevenson et al.	
8,195,290	B2	6/2012	Brockway	
8,224,436	B2	7/2012	Libbus et al.	
8,249,711	B2	8/2012	Libbus et al.	
8,369,943	B2	2/2013	Shuros et al.	

(56) **References Cited**

U.S. PATENT DOCUMENTS

8,386,038	B2	2/2013	Bianchi et al.	
8,401,640	B2	3/2013	Zhao et al.	
8,417,354	B2	4/2013	Zhang et al.	
8,571,654	B2	10/2013	Libbus et al.	
8,577,458	B1	11/2013	Libbus et al.	
8,600,505	B2	12/2013	Libbus et al.	
8,634,921	B2	1/2014	Chavan et al.	
8,688,212	B2	4/2014	Libbus et al.	
8,918,190	B2 *	12/2014	Libbus et al.	607/118
2002/0107553	A1	8/2002	Hill et al.	
2003/0040774	A1	2/2003	Terry et al.	
2003/0171781	A1	9/2003	Florio et al.	
2005/0049655	A1	3/2005	Boveja et al.	
2005/0065553	A1	3/2005	Ben-Ezra et al.	
2005/0125044	A1	6/2005	Tracey	
2005/0131467	A1	6/2005	Boveja	
2005/0267542	A1	12/2005	David et al.	
2006/0015153	A1	1/2006	Gliner et al.	
2006/0100668	A1	5/2006	Ben-David et al.	
2006/0253161	A1	11/2006	Libbus et al.	
2007/0067004	A1	3/2007	Boveja et al.	
2007/0093870	A1	4/2007	Maschino et al.	
2007/0213773	A1	9/2007	Hill et al.	
2007/0233194	A1	10/2007	Craig	
2007/0255320	A1	11/2007	Inman et al.	
2007/0276453	A1	11/2007	Hill et al.	
2008/0021503	A1	1/2008	Whitehurst et al.	
2008/0132983	A1	6/2008	Cohen et al.	
2008/0147140	A1	6/2008	Ternes et al.	
2008/0183258	A1	7/2008	Inman	
2008/0243196	A1	10/2008	Libbus et al.	
2008/0319513	A1	12/2008	Pu et al.	
2009/0030493	A1	1/2009	Colborn et al.	
2009/0118777	A1	5/2009	Iki et al.	
2009/0124848	A1	5/2009	Miazga	
2009/0149900	A1	6/2009	Moffitt et al.	
2009/0248097	A1	10/2009	Tracey et al.	
2009/0270953	A1	10/2009	Ecker et al.	
2010/0010556	A1 *	1/2010	Zhao et al.	607/17
2010/0010603	A1	1/2010	Ben-David et al.	
2010/0016919	A1	1/2010	Hill et al.	
2010/0042173	A1	2/2010	Farazi et al.	
2010/0114197	A1	5/2010	Burnes et al.	
2010/0286740	A1	11/2010	Libbus et al.	
2010/0331908	A1	12/2010	Farazi	
2011/0015692	A1	1/2011	Libbus et al.	
2011/0082514	A1	4/2011	Libbus et al.	
2011/0098796	A1	4/2011	Ben-David et al.	
2011/0224749	A1	9/2011	Ben-David et al.	
2011/0257708	A1	10/2011	Kramer et al.	
2011/0313488	A1	12/2011	Hincapie Ordonez et al.	
2012/0143286	A1	6/2012	Hahn et al.	
2012/0172742	A1	7/2012	Arcot-Krishnamurthy et al.	
2012/0185007	A1	7/2012	Ziegler et al.	
2012/0185010	A1	7/2012	Zhou et al.	
2012/0303080	A1	11/2012	Ben-David et al.	
2013/0158617	A1	6/2013	Libbus et al.	
2013/0158618	A1	6/2013	Libbus et al.	
2013/0238047	A1	9/2013	Libbus et al.	
2013/0289646	A1	10/2013	Libbus et al.	
2013/0304168	A1 *	11/2013	Errico et al.	607/115
2014/0025132	A1	1/2014	Libbus et al.	
2014/0135862	A1	5/2014	Libbus et al.	
2014/0135863	A1	5/2014	Libbus et al.	
2014/0135864	A1	5/2014	Libbus et al.	
2014/0277232	A1	9/2014	Libbus et al.	
2015/0073511	A1	3/2015	Libbus et al.	

OTHER PUBLICATIONS

PCT Application No. PCT/US2012/068205, Search Report and Written Opinion dated Feb. 8, 2013, 15 pages.

PCT Application No. PCT/US2012/068213, Search Report and Written Opinion dated Mar. 15, 2013, 11 pages.

PCT Application No. PCT/US2012/068223, Search Report and Written Opinion dated Apr. 3, 2013, 11 pages.

PCT Application No. PCT/US2013/021964, Search Report and Written Opinion dated Apr. 17, 2013, 10 pages.

PCT Application No. PCT/US2012/068211, Search Report and Written Opinion dated May 7, 2013, 9 pages.

PCT Application No. PCT/US2013/050390, Search Report and Written Opinion dated Nov. 5, 2013.

PCT Application No. PCT/US2013/068541, Search Report and Written Opinion dated Jan. 7, 2014.

Abraham, et al., "Devices in the management of advanced, chronic heart failure," Nature Reviews, vol. 10, pp. 98-110 (Feb. 2013) (Published online Dec. 11, 2012).

Adamson, et al., "Continuous Autonomic Assessment in Patients with Symptomatic Heart Failure: Prognostic Value of Heart Rate Variability Measured by an Implanted Cardiac Resynchronization Device," Circulation, Journal of the American Heart Association, 110, pp. 2389-2394 (2004).

Agostoni, et al., "Functional and Histological Studies of the Vagus Nerve and its Branches to the Heart, Lungs and Abdominal Viscera in the Cat," J. Physiol. 135, pp. 182-205 (1957).

Ajani, et al., "Prevalence of High C-Reactive Protein in Persons with Serum Lipid Concentrations within Recommended Values," Chemical Chemistry, 50:9, pp. 1618-1622 (2004).

Akiyama, et al., "Effects of right and left vagal stimulation on left ventricular acetylcholine levels in the cat," Acta Physiol Scand, 172, pp. 11-16 (2001).

Anand, et al., "C-Reactive Protein in Heart Failure: Prognostic Value and the Effect of Valsartan," Circulation, Journal of the American Heart Association, 112, pp. 1428-1434 (2005).

Anholt, et al., "Recruitment and blocking properties of the CardioFit stimulation lead," Journal of Neural Engineering, 8, pp. 1-6, (2011).

Ardell, et al., "Selective vagal innervation of sinoatrial and atrioventricular nodes in canine heart," Am. J. Physiol. 251 (Heart Circ. Physiol. 20), pp. H764-H773 (1986).

Armour, "Cardiac neuronal hierarchy in health and disease," Am J Physiol Regul Integr Comp Physiol, 287, pp. R262-R271 (2004).

Armour, "Myocardial ischaemia and the cardiac nervous system," Cardiovascular Research, 41, pp. 41-54 (1999).

Armour, JA, "Potential clinical relevance of the 'little brain' on the mammalian heart," Experimental Physiology, vol. 1 93, No. 2, pp. 165-176 (Feb. 2008). Online Publication Date: Nov. 2, 2007. Available at: http://ep.physoc.org/content/93/2/165.long.

Armour, "The little brain on the heart," Cleveland Clinic Journal of Medicine, vol. 74, supp. 1, pp. S48-S51 (Feb. 2007).

Armour, et al., "Functional anatomy of canine cardiac nerves," Acta anat., 91, pp. 510-528 (1975).

Armour, et al., "Localized myocardial responses to stimulation of small cardiac branches of the vagus," American Journal of Physiology, vol. 228, no. 1 pp. 141-148 (Jan. 1975).

Asala, et al., "An electron microscope study of vagus nerve composition in the ferret," Anat Embryol, 175, pp. 247-253 (1986).

Aukrust, et al., "Inflammatory and anti-inflammatory cytokines in chronic heart failure: Potential therapeutic implications," Annals of Medicine, 37, pp. 74-85 (2005).

Author Unknown, "Nerve fiber—Types and Function," www.boddunan.com Available at ww.boddunan.com/education/20-medicine-a-surgery/12730-nerver-fibertypes-and-function.html (Apr. 19, 2010).

Author Unknown, American Diabetes Association, "Standards of Medical Care in Diabetes—2012," Diabetes Care, vol. 35, supplement 1, pp. S11-S63 (Jan. 2012).

Author Unknown, Staff of Adinstruments, "Principles of Nerve Stimulation," Application Note, ADInstruments (Apr. 2002).

Bae, et al., "Gliosis in the Amygdala Following Myocardial Infarction in the Rat," J Vet Med Sci, 72(8), pp. 1041-1045 (2010).

Bernik, et al., "Pharmacological Stimulation of the Cholinergic Antiinflammatory Pathway," J. Exp. Med, vol. 195, No. 6, pp. 781-788 (Mar. 18, 2002).

Berthoud, et al., "Functional and chemical anatomy of the afferent vagal system," Autonomic Neuroscience: Basic and Clinical, 85, pp. 1-17 (2000).

(56) **References Cited**

OTHER PUBLICATIONS

Bhagat, et al., "Differential Effect of Right and Left Vagal Stimulation on Right and Left Circumflex Coronary Arteries," S A Medical Journal, 50, pp. 1591-1594 (1976).
Biasucci, et al., "Elevated Levels of C-Reactive Protein at Discharge in Patients with Unstable Angina Predict Recurrent Instability," Circulation,Journal of the American Heart Association, 99, pp. 855-860 (1999).
Bibevski, et al., "Evidence for impaired vagus nerve activity in heart failure," Heart Fail Rev, 16, pp. 129-135 (2011).
Bibevski, et al., "Ganglionic Mechanisms Contribute to Diminished Vagal Control in Heart Failure," Circulation, Journal of the American Heart Association, 99, pp. 2958-2963 (1999).
Bilgutay, et al., "Vagal Tuning a new concept in the treatment of supraventricular arrhythmias, angina pectoris, and heart failure," Journal of Thoracic and Cardiovascular Surgery, vol. 56, No. 1, pp. 71-82 (Jul. 1968).
Binkley, et al., "Parasympathetic Withdrawal Is an Integral Component of Autonomic Imbalance in Congestive Heart Failure: Demonstration in Human Subjects and Verification in a Paced Canine Model of Ventricular Failure," JACC, vol. 18, No. 2, pp. 464-472 (Aug. 1991).
Bois, et al., "Mode of action of bradycardic agent, S 16257, on ionic currents of rabbit sinoatrial node cells," Abstract, British Journal of Pharmacology, 118(4):1051-7 (1996).
Bonaz, et al., "Vagus nerve stimulation: From epilepsy to the cholinergic anti-inflammatory pathway," Neurogastroenterology & Motility, pp. 1-14 (2013).
Borggrefe, et al., "Vagal Stimulation Devices," ESC Congress 2010 (2010).
Borovilkova, et al., "Vagus nerve stimulation attenuates the systemic inflammatory response to endotoxin," Nature, vol. 405, pp. 458-462 (May 25, 2000).
Brack, et al., "Mechanisms underlying the autonomic modulation of ventricular fibrillation initiation—tentative prophylactic properties in vagus nerve stimulation on malignant arrhythmias in heart failure," Heart Fail Rev (Published online Jun. 8, 2012).
Bronzino, "Biomedical Engineering Fundamentals," CRC Press, Chapter 30, pp. 30-10-30-15 (Apr. 2006).
Buschman, et al., "Heart Rate Control Via Vagus Nerve Stimulation," Neuromodulation, vol. 9, No. 3, pp. 214-220 (2006).
Butterwick, et al., "Tissue Damage by Pulsed Electrical Stimulation," IEEE Transactions on Biomedical Engineering, vol. 54, No. 12, pp. 2261-2267 (Dec. 2007).
Calkins, et al., "Comparison of Responses to Isoproterenol and Epinephrine During Head-Up Tilt in Suspected Vasodepressor Syncope," the American Journal of Cardiology, vol. 67 pp. 207-209 (Jan. 15, 1991).
Castoro, et al., "Excitation properties of the right cervical vagus nerve in adult dogs," Experimental Neurology, 227 (pp. 62-68 (2011).
Chapleau, et al., "Methods of assessing vagus nerve activity and reflexes," Heart Fail Rev, 16, pp. 109-127 (2011).
Chen, et al., "National and Regional Trends in Heart Failure Hospitalization and Mortality Rates for Medicare Beneficiaries, 1998-2008," JAMA, vol. 306, No. 15 (Oct. 19, 2011).
Chen, et al., "Role of Atrial Electrophysiology and Autonomic Nervous System in Patients with Supraventricular Tachycardia and Paroxysmal Artrial Fibrillation," J Am Coll Cardiol, vol. 32, No. 3, pp. 732-738 (Sep. 1998).
Cheng, et al., "Long-term Outcomes in Individuals with Prolonged PR Interval or First-Degree Atrioventricular Block," JAMA, vol. 301, No. 24 pp. 2571-2577 (Jun. 24, 2009).
Chiou, et al., "Effects of Continuous Enhanced Vagal Tone and Dual Atrioventricular Node and Accessory Pathways," Circulation, Journal of the American Heart Association, 107, pp. 2583-2588 (2003).
Cohen, et al., "Histopathology of the stimulated Vagus nerve: Primum non nocere," Heart Fail Rev, 16, pp. 163-169 (2011).
Colombo, et al., "Comparison between spectral analysis and the phenylephrine methods for the assessment of baroreflex sensitivity in chronic heart failure," Clinical Science, 97, pp. 503-513 (1999).
Cryan, et al., "Animal models and mood disorders: recent developments," Current Opinion in Psychiatry, 20, pp. 1-7 (2007).
Das, "Vagal nerve stimulation in prevention and management of coronary heart disease," World J. Cardiol, 3(4), pp. 105-110 (Apr. 26, 2011).
De Castro, et al., "Parasympathetic-mediated atrial fibrillation during tilt test associated with increased baroreflex sensitivity," the European Society of Cardiology, Europace, 8, pp. 349-351 (2006).
De Ferrari, et al., "Baroreflex Sensitivity Predicts Long-Term Cardiovascular Mortality After Myocardial Infarction Even in Patients with Preserved Left Ventricular Function," Journal of the American College of Cardiology, vol. 50, No. 24, pp. 2285-2290 (2007).
De Ferrari, et al., "Chronic Vagal Stimulation in Patients with Congestive Heart Failure," 31st Annual International Conference of the IEE EMBS (2009).
De Ferrari, et al., "Chronic vagus nerve stimulation: a new and promising therapeutic approach for chronic heart failure," European Heart Journal, 32, pp. 847-855 (2011).
De Ferrari, et al., "Vagus nerve stimulation: from pre-clinical to clinical application: challenges and future directions," Heart Fail Rev, 16, pp. 195-203 (2011) (Published Online Dec. 17, 2010).
De Jonge, et al., "Stimulation of the vagus nerve attenuates macrophage activation by activating the Jak2-STAT3 signaling pathway," Nature Immunology, vol. 6, No. 8, pp. 844-852 (Aug. 2005).
Desai, et al., "Pharmacologic modulation of parasympathetic activity in heart failure," Heart Fail Rev, 16, pp. 179-193 (Published online: Oct. 6, 2010) (2011).
Dickerson, et al., "Parasympathetic neurons in the cranial medial ventricular fat pad on the dog heart selectively decrease ventricular contractility," Journal of the Autonomic Nervous System, 70, pp. 129-141 (1998).
Dunlap, et al., "Mechanisms of altered vagal control in heart failure: influence of muscarinic receptors and acetylcholinesterase activity," Am J Physiol Heart Circ Physiol, 285, pp. H1632-H1640 (Jun. 26, 2003).
Elsenbruch, et al., "Heart Rate Variability During Waking and Sleep in Healthy Males and Females," Sleep, vol. 22, No. 8, pp. 1067-1071 (1999).
Euler, et al., "Acetylcholine release by a stimulus train lowers atrial fibrillation threshold," Am. J Physiol. 253 (Heart Circ. Physiol, 22), pp. H863-H868 (1987).
Evans, et al., "Histological and functional studies on the fibre composition of the vagus nerve of the rabbit," Journal of Anatomy, 130, pp. 139-151 (1954).
Fallen, "Vagal Afferent Stimulation as a Cardioprotective Strategy? Introducing the Concept," A.N. E., vol. 10, No. 4 (Oct. 2005).
Fan, et al., "Transvenous vagus nerve stimulation: A potential heart failure therapy is feasible in humans," JACC, vol. 55, issue 10A, pp. E152-E153 (2010).
Fazan, et al., "Diabetic Peripheral Neuropathies: A Morphometric Overview," Int. J. Morphol, 28(1), pp. 51-64 (2010).
Feinauer, et al., "Ouabain enhances release of acetylcholine in the heart evoked by unilateral vagal stimulation," Arch Pharmacol, 333, pp. 7-12 (1986).
Fonarow, et al., "Incremental Reduction in Risk of Death Associated with Use of Gudeline-Recommended Therapies in Patients with Heart Failure: A Nested Case-Control Analysis of IMPROVE HF," J Am Heart Assoc, 1, pp. 16-26 (2012).
Ford, et al., "The effects of electrical stimulation of myelinated and non-myelinated vagal fibres on heart rate in the rabbit," J. Physiol. 380, pp. 341-347 (1986).
Furukawa, et al., "Effects of Verapamil, Zatebradine, and E-4031 on the Pacemaker Location and Rate in Response to Sympathetic Stimulation in Dog Hearts," The Journal of Pharmacology and Experimental Therapeutics, vol. 289, No. 3, pp. 1334-1342 (1999).
Furukawa, et al., "Selective inhibition by zatebradine and discrete parasympathetic stimulation of the positive chronotropic response to sympathetic stimulation in anesthetized dogs," Abstract, Journal of Pharmacology & Experimental Therapeutics, 272(2):744-9 (1995).
Gatti, et al., "Can neurons in the nucleus ambiguus selectively regulate cardiac rate and atrio-ventricular conduction?" Journal of the Autonomic Nervous System, 57, pp. 123-127 (1996).

(56) **References Cited**

OTHER PUBLICATIONS

Gatti, et al., "Vagal control of left ventricular contractility is selectively mediated by a cranioventricular intracardiac ganglion in the cat," Journal of the Autonomic Nervous System, 66, pp. 138-144 (1997).
Gibbons, et al., "Neuromodulation targets intrinsic cardiac neurons to attenuate neuronally mediated atrial arrhythmias," Am J Physiol Regul Integr Comp Physiol 302: R357-R364 (2012) (First published Nov. 16, 2011).
Gottdiener, et al., "Predictors of Congestive Heart Failure in the Elderly: The Cardiovascular Heatlh Study," Journal of the American College of Cardiology, vol. 35, No. 6, pp. 1628-1637 (2000).
Gray, et al., "Parasympathetic control of the Heart. II. A novel interganglionic intrinsic cardiac circuit mediates neural control of heart rate," J. Appl Physiol, 96, pp. 2273-2278 (2004).
Gray, et al., "Parasympathetic control of the Heart. III. Neuropeptide Y-immunoreactive nerve terminals synapse on three populations of negative chronotropic vagal preganglionic neurons," J. Appl Physiol, 96, pp. 2279-2287 (2004).
Grill, "Chapter 14—Principles of Electric Field Generation for Stimulation of the Central Nervous System," Neuromodulation, Academic Press (2009).
Guilleminault, et al., "Cyclical Variation of the Heart Rate in Sleep Apnoea Syndrome," The Lancet, pp. 126-131 (Jan. 21, 1984).
Hardwick, et al., "Chronic myocardial infarction induces phenotypic and functional remodeling in the guinea pig cardiac plexus," Am J Physiol Regulatory Integrative Comp Physiol, 295, pp. 1926-1933 (2008).
Hardwick, et al., "Remodeling of the guinea pig intrinsic cardiac plexus with chronic pressure overload," Am J Physiol Regulatory Integrative Comp Physiol, 297, pp. 859-866 (2009).
Hauptman, et al., "The vagus nerve and autonomic imbalance in heart failure: past, present, and future," Heart Fail Rev, 16, pp. 97-99 (2011).
Hellyer, et al., "Autonomic nerve activity and blood pressure in ambulatory dogs," Heart Rhythym, vol. 11(2), pp. 307-313 (Feb. 2014).
Hirooka, et al., "Imbalance of central nitric oxide and reactive oxygen species in the regulation of sympathetic activity and neural mechanisms of hypertension," Am J Physiol Regulatory Integration Comp Physiol, 300, pp. 818-826 (2011).
Hoffman, et al., "Vagus Nerve Components," Anat Rec, 127, pp. 551-568 (1957).
Hu et al., "Role of sympathetic nervous system in myocardial ischemia injury: Beneficial or deleterious?" Letters to the Editor, Elsevier Ireland Ltd. (Mar. 27, 2012).
Hua, et al., "Left vagal stimulation induces dynorphin release and suppresses substance P release from the rat thoracic spinal cord during cardiac ischemia," Am J Physiol Regulatory Integration Comp Physiol, 287, pp. 1468-1477 (2004).
Huston, et al., "Splenectomy inactivates the cholinergic antiinflammatory pathway during lethal endotoxemia and polymicrobial sepsis," J. Exp. Med, vol. 203, No. 7 pp. 1623-1628 (Jun. 19, 2006).
Huston, et al., "Transcutaneous vagus nerve stimulation reduces serum high mobility group box 1 levels and improves survival in murine sepsis," Crit Care Med, vol. 35, No. 12, pp. 2762-2768 (2007).
Ingemansson, et al., "Autonomic modulation of the atrial cycle length by the head up tilt test: non-invasive evaluation in patients with chronic atrial fibrillation," Heart, 80, pp. 71-76 (1998).
Ito, et al., "Efferent sympathetic and vagal innervation of the canine right ventricle," Circulation, Journal of the American Heart Association, vol. 90, pp. 1469-1468 (1994).
Jacques, et al., "Spinal Cord Stimulation Causes Potentiation of Right Vagus Nerve Effects on Atrial Chronotropic Function and Repolarization in Canines," Journal of Cardiovascular Electrophysiology, vol. 22, No. 4, pp. 440-447 (Apr. 2011).
Jaenisch, et al., "Respiratory muscle training improves baroreceptor sensitivity, decrease sympathetic tonus and increase vagal effect in rats with heart failure," European Heart Journal, 32 (Abstract Supplement, pp. 976 (2011).
Jammes, et al., "Afferent and efferent components of the bronchial vagal branches in cats," Journal of the Autonomic Nervous System, 5, pp. 165-176 (1982).
Janabi, et al., "Oxidized LDL—Induced NF-kB Activation and Subsequent Expression of Proinflammatory Genes are Defective in Monocyte-Derived Macrophages from CD36-Deficient Patients," Arterioscler Thromb Vasc Biol., 20:1953-1960 (2000).
Janse, et al., "Effects of unilateral stellate ganglion stimulation and ablation on electrophysiologic changes induced by acute myocardial ischemia in dogs," Circulation, Journal of the American Heart Association, 72, pp. 585-595 (1985).
Jessup, et al., "2009 Focused Update: ACCF/AHA Guidelines for the Diagnosis and Management of Heart Failure in Adults," Circulation, Journal of the American Heart Association, vol. 119, pp. 1977-2016 (2009).
Johnson, et al., "Parasympathetic control of the heart. I. An interventriculo-septal ganglion is the major source of the vagal intracardiac innervation of the ventricles," J Appl Physiol, 96, pp. 2265-2272 (2004).
Kakinuma, et al., "Cholinoceptive and cholinergic properties of cardiomyocytes involving an amplification mechanism for vagal efferent effects in sparsely innervated ventricular myocardium," FEBS Journal, 276, pp. 5111-5125 (2009).
Kalman, "Specific effects of zatebradine on sinus node function: suppression of automaticity, prolongation of sinoatrial conduction and pacemaker shift in the denervated canine heart," Abstract, Journal of Pharmacology & Experimental Therapeutics, 272(1):85-93 (1995).
Kaneko, et al., "C-Reactive Protein in Dilated Cardiomyopathy," Cardiology, 91, pp. 215-219 (1999).
Katare, et al., "Vagal nerve stimulation prevents reperfusion injury through inhibition of opening of mitochondrial permeability transition pore independent of bradycardiac effect," The Journal of Thoracic and Cardiovascular Surgery, vol. 137, No. 1, pp. 223-231 (2009).
Katz, et al., "Diseases of the heart in the Works of Hippocrates," Br Heart J, 24, pp. 257-264 (1962).
Kawada, et al., "High-frequency dominant depression of peripheral vagal control of heart rate in rats with chronic heart failure," Acta Physiol 207, 494-502 (2013).
Kawada, et al., "Vagal stimulation suppresses isschemia-induced myocardial interstitial norepinephrine release," Life Sciences, 78, pp. 882-887 (2006).
Kawashima, "The autonomic nervous system of the human heart with special reference to its origin, course, and peripheral distribution," Anat Embryol, 209, pp. 425-438 (2005).
Klein et al., "Vagus nerve stimulation: A new approach to reduce heart failure," Cardiology Journal, vol. 17, iss. 6, pp. 638-643 (2010).
Kliks, et al., "Influence of Sympathetic Tone on Ventricular Fibrillation Threshold During Experimental Coronary Occlusion," The American Journal of Cardiology, vol. 36, pp. 45-49 (Jul. 1975).
Kolman, et al., "The effect of vagus nerve stimulation upon vulnerability of the canine ventricle: role of sympathetic-parasympathetic interactions," Journal of the American Heart Association, 52, pp. 578-585 (1975).
Kong, et al., "Optimizing the Parameters of Vagus Nerve Stimulation by Uniform Design in Rats with Acute Myocardial Infarction," PLOS One, vol. 7, issue 11 (Nov. 2012).
Koopman, et al., "Pilot study of stimulation of the cholinergic antiinflammatory pathway with an implantable vagus nerve stimulation device in patients with rheumatoid arthritis," Abstract (2012).
Kulbertus, et al., ed., "Neurocardiology," Futura Publishing Co., pp. 13 ("Anatomy of the Cardiac Efferent Innvervation"); 61-63 ("Autonomic Neural Control"); 87, 89, 92-93 ("Sympathetic-Parasympathetic Interactions"); 183, 187 ("Parasympathetic Nervous System"); 104 (1988).
La Rovere, et al., "Baroreflex Sensitivity and Heart Rate Variability in the Identification of Patients at Risk for Life-Threatening Arrhythmias: Implications for Clinical Trials," Circulation, Journal of the American Heart Association, 103, pp. 2072-2077 (2001).
La Rovere, et al., "Baroreflex sensitivity and heart-rate variability in prediction of total cardiac mortality after myocardial infarction.

(56) **References Cited**

OTHER PUBLICATIONS

ATRAMI (Autonomic Tone and Reflexes After Myocardial Infarction) Investigators," Lancet, 351(9101), pp. 478-484 (Feb. 14, 1998).
Lane, et al., "Prediction and Prevention of Sudden Cardiac Death in Heart Failure," Heart, 91, pp. 674-680 (2005).
Lechat, et al., "Heart rate and Cardiac Rhythm Relationships with Bisoprolol Benefit in Chronic Heart Failure in CIBIS II Trial," Circulation, Journal of American Heart Association, 103, pp. 1428-1433 (2001).
Lewis, et al., "Vagus nerve stimulation decreases left ventricular contractility in vivo in the human and pig heart," Journal of Physiology, 534, pp. 547-552 (2001).
Li, et al., "Early vagal stimulation markedly prevented cardiac dysfunction in rats after acute myocardial infarction in addition to suppressing arrhythmic death," European Heart Journal, 32 (Abstract Supplement), pp. 297-298 (2011).
Li, et al., "Inflammatory cytokines and nitric oxide in heart failure and potential modulation by vagus nerve stimulation," Heart Fail Rev, 16, pp. 137-145 (2011).
Li, et al., "Low-Level Vagosympathetic Stimulation. A Paradox and Potential New Modality for the Treatment of Focal Atrial Fibrillation," Circ Arrhythm Electrophysiol, Journal of American Heart Association, 2, pp. 645-651 (2009).
Li, et al., "Restoration of vagal tone by donepezil, on top of losartan treatment, markedly suppresses ventricular dysfunction and improves long-term survival in chronic heart failure rats," European Heart Journal, 32 (Abstract Supplement), pp. 642 (2011).
Li et al., "Vagal Nerve Stimulation Markedly Improves Long-Term Survival After Chronic Heart Failure in Rats," Circulation: Journal of the American Heart Association, vol. 109, iss. 1, pp. 120-124 (Jan. 2004). Online publication date: Dec. 8, 2003.
Libby, et al., "Inflammation and Atherosclerosis," Circulation, Journal of the American Heart Association, 105, pp. 1135-1143 (2002).
Liu, et al., "Differing sympathetic and vagal effects on atrial fibrillation in dogs: role of refractoriness heterogeneity,"Am. J. Physiol. 273 (Heart Circ. Physiol. 42), pp. H805-H816 (1997).
Lo, et al., "Paradoxical long-term proarrhythmic effects after ablating the 'head station' ganglionated plexi of the vagal innervation to the heart," Heart Rhythm, vol. 10, No. 5, pp. 751-757 (May 2013).
Lohmeier, et al., "Prolonged Activation of the Barorelfex Produces Sustained Hypotension," Hypertension, Journal of the American Heart Association, 43, pp. 306-311 (2004).
Lu, et al., "Vagal nerve stimulation protects cardiac injury by attenuating mitochondrial dysfunction in a murine burn injury model," J. Cell. Mol. Med., vol. 17, No. 5, pp. 664-671 (2013).
Ma, et al., "Analysis of afferent, central, and efferent components of the baroreceptor reflex in mice," Am J Physiol Regulatory Integration Comp Physiol, 283, pp. 1033-1040 (2002).
Maj, et al., "P5775: Autonomic imbalance and circulating androgens and estrogens in men with systolic heart failure," European Heart Journal, 32 (Abstract Supplement), pp. 1090 (2011).
Malkin, et al., "Life-saving or life-prolonging? Interpreting trial data and survival curves for patients with congestive heart failure," The European Journal of Heart Failure, 7, pp. 143-148 (2005).
Mann, "Chapter 12—Peripheral Nerves," The Nervous System in Action, michaeldmann.net/mann12.html, (Jul. 2011).
Mann, "Inflammatory Mediators and the Failing Heart: Past, Present, and the Foreseeable Future," Circ Res., 91, pp. 988-998 (2002).
Mann, "Stress-Activated Cytokines and the Heart: From Adaptation to Maladaptation," Annu. Rev. Physiol., 65, pp. 81-101 (2003).
Martin-Portugues, et al., "Histopathologic features of the vagus nerve after electrical stimulation in swine," Histol Histopathol, 20, pp. 851-856 (2005).
Martins, et al., "Distribution of Local Repolarization Changes Produced by Efferent Vagal Stimulation in the Canine Ventricles," JACC, vol. 2, No. 6, pp. 1191-1199 (Dec. 1983).
Massari, et al., "Neural control of left ventricular contractility in the dog heart: synaptic interactions of negative inotropic vagal preganglionic neurons in the nucleus ambiguus and tyrosine hydroxylase immunoreactive terminals," Brain Research, 802, pp. 205-220 (1998).
May, et al., "P564: Long-term prediction of all-cause mortality in diabetic autonomic neuropathy: simple function tests or 24-hour heart rate variability (HRV)?" European Heart Journal, 32 (Abstract Supplement, pp. 64 (2011).
Mei, et al., "The Composition of the Vagus Nerve of the Cat," Cell Tissue Res., 209, pp. 423-431 (1980).
Merrill, et al., "Electrical stimulation of excitable tissue: design of efficacious and safe protocols," Journal of Neuroscience Methods, 141, pp. 171-198 (2005).
Mortara, et al., "Arterial Baroreflex Modulation of Heart Rate in Chronic Heart Failure," Circulation, Journal of the American Heart Association, vol. 96, No. 10, pp. 3450-3458 (Nov. 18, 1997).
Murakawa, et al., "Effect of Cervical Vagal Nerve Stimulation on Defibrillation Energy," Jpn Heart J, 44, pp. 91-100 (Jan. 2003).
Naito, "Effects of zatebradine and propranolol on canine ischemia and reperfusion-induced arrhythmias," European Journal of Pharmacology, 388, pp. 171-176 (2000).
Nakajima, et al., "Autonomic Control of the Location and Rate of the Cardiac Pacemaker in the Sinoatrial Fat Pad of Parasympathetically Denervated Dog Hearts," Journal of Cardiovascular Electrophysiology, vol. 13, No. 9 pp. 896-901 (Sep. 2002).
Nearing, et al., "Crescendo in Depolarization and Repolarization Heterogeneity Heralds Development of Ventricular Tachycardia in Hospitalized Patients with Decompensated Heart Failure," Circulation Arrhythmia and Electrophysiology, Journal of the American Heart Association, 5, pp. 84-90 (2012).
Nihei, et al., "Decreased Vagal Control Over Heart Rate in Rats with Right-Sided Congestive Heart Failure—Downregulation of Neuronal Nitric Oxide Synthase," Circ J, 69, pp. 493-499 (2005).
Ninomiya, "Direct Evidence of Nonuniform Distribution of Vagal Effects on Dog Atria," Circulation Research, vol. XIX, pp. 576-583 (Sep. 1966).
Nolan, et al., "Prospective Study of Heart Rate Variability and Mortality in Chronic Heart Failure: Results of the United Kingdom Heart Failure Evaluation and Assessment of Risk Trial (UK-Heart)," Circulation, Journal of the American Heart Association, 98, pp. 1510-1516 (1998).
Ochoa, et al., "P2497: Effects of insulin resistance on resting heart rate, baroreflex sensitivity and indices of autonomic cardiovascular modulation in individuals with high blood pressure levels," European Heart Journal, 32 (Abstract Supplement, pp. 431-432 (2011).
Ogawa, et al., "Left Stellate Ganglion and Vagal Nerve Activity and Cardiac Arrhythmias in Ambulatory Dogs with Pacing-Induced Congestive Heart Failure," Journal of the American College of Cardiology, vol. 50, No. 4, pp. 335-444 (2007).
Okada, et al., "Cyclic Stretch Upregulates Production of Interleukin-8 and Monocyte Chemotactic and Activating Factor/Monocyte Chemoattractant Protein-1 in Human Endothelial Cells," Arterioscler Thromb Vasc Biol., 18, pp. 894-901 (1998).
Oliveira, et al., "Effects of vagal stimulation on induction and termination of atrial fibrillation in an in vivo rabbit heart model," Rev Port Cardiol, 29(03), pp. 375-389 (2010).
Olshansky, et al., "Parasympathetic Nervous System and Heart Failure: Pathophysiology and Potential Implications for Therapy," Circulation, Journal of the American Heart Association, 118, pp. 863-871 (2008).
Onkka, et al., "Sympathetic nerve fibers and ganglia in canine cervical vagus nerves: Localization and quantitation," Heart Rhythm, vol. 10, No. 4, pp. 585-591 (Apr. 2013).
Ordelman, et al., "Selectivity for Specific Cardiovascular Effects of Vagal Nerve Stimulation with a Multi-Contact Electrode Cuff," IEEE, pp. 1-6 (2011).
Packer, et al., "Effect of Carvedilol on Survival in Severe Chronic Heart Failure," The New England Journal of Medicine, vol. 344, No. 22, pp. 1651-1658 (May 31, 2001).
Pavlov, et al., "Central muscarinic cholinergic regulation of the systemic inflammatory response during endotoxemia," PNAS, vol. 103, No. 13, pp. 5219-5223 (Mar. 28, 2006).

(56) **References Cited**

OTHER PUBLICATIONS

Pavlov, et al., "Controlling inflammation: the cholinergic anti-inflammatory pathway," Biochemical Society Transactions, vol. 34, part 6, pp. 1037-1040 (2006).

Peckham, et al., "Chapter 18—Implantable Neural Stimulators," Neuromodulation, Academic Press (2009).

Pina, et al., "The Predictive Value of Biomarkers in Heart Failure," Medscape Education Cardiology, Available at http://www.medscape.org/viewarticle/765328 (CME Released: Jun. 15, 2012).

Pitzalis, et al., "Comparison Between Noninvasive Indices of Baroreceptor Sensitivity and the Phenylephrine Method in Post-Myocardial Infarction Patients," Circulation, Journal of the American Heart Association, 97, pp. 1362-1367 (1998).

Poole-Wilson, "Relation of Pathophysiologic Mechanisms to Outcome in Heart Failure," JACC, vol. 22, No. 4 (supplement A), pp. 22A-9A (Oct. 1993).

Pye, et al., "Study of serum C-reactive protein concentration in cardiac failure," Br Heart J, 63, pp. 228-230 (1990).

Rademacher, et al., "P5878: Multidimensional holter-based analysis of cardiac autonomic regulation predicts early AF recurrence after electrical cardioversion," European Heart Journal, 32 (Abstract Supplement), pp. 1116-1117 (2011).

Randall, et al., "Regional vagosympathetic control of the heart," American Journal of Physiology, vol. 227, No. 2, pp. 444-452 (1974).

Randall, et al., "Selective Vagal Innervation of the Heart," Annals of Clinical and Laboratory Science, vol. 16, No. 3, pp. 198-208 (1986).

Raymond, et al., "Elevated interleukin-6 levels in patients with asymptomatic left ventricular systolic dysfunction," American Heart Journal, vol. 141, No. 3, pp. 435-438 (Mar. 2001).

Rhee, et al., "Effects of suprathreshold vagal stimulation on stellate ganglion nerve activity in ambulatory dogs," 33rd Annual Scientific Sessions, Heart Rhythm, Presentation Abstract (2012).

Riccio, et al., "Interganglionic segregation of distinct vagal afferent fibre phenotypes in guinea-pig airways," Journal of Physiology, 495.2, pp. 521-530 (1996).

Riddle, et al., "Epidemiologic Relationships Between A1C and All-Cause Mortality During a Median 3.4-Year Follow-up of Glycemic Treatment in the ACCORD Trial," Diabetes Care, vol. 33, No. 5, pp. 983-990 (May 2010).

Ridker, "C-Reactive Protein: A Simple Test to Help Predict Risk of Heart Attack and Stroke, " Journal of the American Heart Association, 108, pp. e81-e85 (2003).

Ridker, et al., "Comparison of C-Reactive Protein and Low-Density Lipoprotein Cholesterol Levels in the Prediction of First Cardiovascular Events," New England Journal of Medicine, vol. 347, No. 20, pp. 1557-1566 (Nov. 14, 2002).

Ridker, et al., "C-Reactive Protein and Other Markers of Inflammation in the Prediction of Cardiovascular Disease in Women," The New England Journal of Medicine, vol. 342, No. 12, pp. 836-841 (Mar. 23, 2000).

Ridker, et al., "Inflammation, Pravastatin, and the Risk of Coronary Events After Myocardial Infarction in Patients With Average Cholesterol Levels," Circulation, Journal of the American Heart Association, 98, pp. 839-844 (1998).

Roger, et al., "Heart Disease and Stroke Statistics-2011 Update: A Report from the American Heart Association," Circulation, Journal of the American Heart Association Available at http://circ.ahajournals.org/content/123/4/e18 (2010).

Romanovsky, et al., "The vagus nerve in the thermoregulatory response to systemic inflammation," Am. J. Physiol., 273, pp. R407-R413 (1997).

Rossi, et al., "Epicardial ganglionated plexus stimulation decreases postoperative inflammatory response in humans," Heart Rhythm, vol. 9, No. 6, pp. 943-950 (Jun. 2012).

Rouse, et al., "The haemodynamic actions of ZENCA ZD7288, a novel sino-atrial node function modulator, in the exercising beagle: a comparison with zategradine and propranolol," Abstract, British Journal of Pharmacology, 113(3):1071-7 (1994).

Rozman, et al., "Heart function influenced by selective mid-cervical left vagus nerve stimulation in a human case study," Hypertension Research, 32, pp. 1041-1043 (2009).

Rutecki, "Anatomical, Physiological and Theoretical Basis for the Antiepileptic Effect of Vagus Nerve Stimulation," Epilepsia, 31 (suppl. 2), pp. S1-S6 (1990).

Sabbah, et al., "3722: Vagus nerve stimulation improves left ventricular function in heart failure: results of a 6 month investigation with a cross-over design in dogs with experimental heart failure," European Heart Journal, 32 (Abstract Supplement), pp. 642 (2011).

Sabbah, et al., "Baroreflex Activation Therapy for the Treatment of Heart Failure," Presentation available at http://www.cvrx.com/wp/wp-content/uploads/2012/04/Dr.-Sabbah-Slides.pdf (2012).

Sabbah, et al., "Chronic Electrical Stimulation of the Carotid Sinus Baroreflex Improves Left Ventricular Function and Promotes Reversal of Ventricular Remodeling in Dogs with Advanced Heart Failure," Circulation Heart Failure, Journal of the American Heart Association, 4, pp. 65-70 (2011).

Sabbah et al., "Vagus nerve stimulation in experimental heart failure," Heart Failure Reviews, vol. 16, No. 2, pp. 171-178 (Mar. 2011). Online Publication Date: Dec. 3, 2010.

Samara, et al., "The Effects of Cardiac Resyhchronization Therapy on Chronotropic Incompetence in Patients Intolerant of Beta Antagonist Therapy," Journal of Cardiac Failure, vol. 17, No. 8S, pp. S-54-S55 (Aug. 2011).

Sanner, et al., "P4743: Prediction of cardiovascular risk from nocturnal pulse wave signal using the autonomic state indicator (ASI) technology," European Heart Journal, 32 (Abstract Supplement), pp. 839 (2011).

Sato, et al., "Serial Circulating Concentrations of C-Reactive Protein, Interleukin (IL)-4, and IL-6 in Patients with Acute Left Heart Decompensation," Clin. Cardiol. 22, pp. 811-813 (1999).

Schauerte, "Time for Change: Cardiac neurophysiology meets cardiac electrophysiology," Editorial Commentary, Heart Rhythm Society (2013).

Schiereck, et al., "AV blocking due to asynchronous vagal stimulation in rats," Am J Physiol Heart Circ Physiol, 278, pp. H67-H73 (2000).

Schocken, et al., "Prevalence and Mortality Rate of Congestive Heart Failure in the United States," JACC, vol. 20, No. 2, pp. 301-306 (Aug. 1992).

Schwartz, "Vagal Stimulation for Heart Diseases: From Animals to Men," Circulation Journal, vol. 75, pp. 20-27 (Jan. 2011).

Schwartz, "Vagal stimulation for heart failure," Current Opinion in Cardiology, 26, pp. 51-54 (2011).

Schwartz, "Vagal stimulation for the treatment of heart failure: a translational success story," Heart, vol. 98, No. 23, pp. 1687-1690 (2012).

Schwartz, et al. Vagal stimulation for heart failure: Background and first in-man study, Heart Rhythm, 6, 11 suppl., pp. S76-81 (Nov. 2009).

Schwartz, et al., "Autonomic mechanisms and sudden death. New insights from analysis of baroreceptor reflexes in conscious dogs with and without myocardial infarction," Circulation, Journal of the American Heart Association, 78, pp. 969-979 (1988).

Schwartz, et al., "Effects of Unilateral Cardiac Sympathetic Denervation on the Ventricular Fibrillation Threshold," The American Journal of Cardiology, vol. 37, pp. 1034-1040 (Jun. 1976).

Schwartz, et al., "Long term vagal stimulation in patients with advanced heart failure. First experience in man," European Journal of Heart Failure, 10, pp. 884-891 (2008).

Schwartz, et al., "Sympathetic-parasympathetic interaction in health and disease: abnormalities and relevance in heart failure," Heart Fail Rev, 16, pp. 101-107 (2011).

Seta, et al., "Basic Mechanisms in Heart Failure: The Cytokine Hypotehsis," Journal of Cardiac Failure, vol. 2, No. 3, pp. 243-249 (1996).

Sha, et al., "Low-Level Right Vagal Stimulation: Anticholinergic and Antiadrenergic Effects," J Cardiovasc Electrophysiol, pp. 1-7 (Feb. 2011).

Shamoon, et al., The Diabetes Control and Complications Trial Research Group, "The effect of intensive treatment of diabetes on the development and progression of long-term complications in insulin-

(56) **References Cited**

OTHER PUBLICATIONS

dependent diabetes mellitus," The New England Journal of Medicine, vol. 329, No. 14, pp. 977-986 (Sep. 30, 1993).
Shannon, "A Model of Safe Levels for Electrical Stimulation," IEEE Transactions on Biomedical Engineering, vol. 39, No. 4, pp. 424-426 (Apr. 1992).
Shen, et al., "Continuous Low-Level Vagus Nerve Stimulation Reduces Stellate Ganglion Nerve Activity and Paroxysmal Atrial Tachyarrhythmias in Ambulatory Canines," Circulation, Journal of the American Heart Association, 123, pp. 2204-2212 (2011).
Shen, et al., "Low-level vagus nerve stimulation upregulates small conductance calcium-activated potassium channels in the stellate ganglion," Heart Rhythm, vol. 10, No. 6, pp. 910-915 (2013).
Shinohara, et al., "Heart Failure Decreases Nerve Activity in the Right Atrial Ganglionated Plexus," J Cardiovasc Electrophysiol, pp. 1-9 (2011).
Shioi, et al., "Increased Expression of Interleukin-1B and Monocyte Chemotactic and Activating Factor/Monocyte Chemoattractant Protein-1 in the Hypertrophied and Failing Heart with Pressure Overload," Circ Res., 81, pp. 664-671 (1997).
Singal, et al., "The role of oxidative stress in the genesis of heart disease," Cardiovascular Research, 40, pp. 426-432 (1998).
Spuck, et al., "Right-sided vagus nerve stimulation in humans: An effective therapy?" Epilepsy Research, pp. 1-3 (2008).
Stein, et al., "A Simple Method to Identify Sleep Apnea Using Holter Recordings," J Cardiovasc Electrophysiol, vol. 14, pp. 467-473 (May 2003).
Stein, et al., "Feasibility of Using Mobile Cardiac Outpatient Telemetry (MCOT) to Identify Severe Sleep Disorders" (2009).
Stieber, et al., "Bradycardic and proarrhythmic properties of sinus node inhibitors," Abstract, Molecular Pharmacology, 69(4):1328-37 (2006).
Taylor, et al., "The unequal influences of the left and right vagi on the control of the heart and pulmonary artery in the rattlesnake, *Crotalus durissus*," The Journal of Experimental Biology, 212, pp. 145-151 (2009).
Thayer, et al., "The role of vagal function in the risk for cardiovascular disease and mortality," Biological Psychology, 74, pp. 224-242 (2007).
Thollon, et al., "Electrophysiological effects of S 16257, a novel sino-atrial node modulator, on rabbit and guinea-pig cardiac preparations: comparison with UL-FS 49," Abstract, British Journal of Pharmacology, 112(1):37-42 (1994).
Tosato, et al., "Quasi-trapezoidal pulses to selectively block the activation of intrinsic laryngeal muscles during vagal nerve stimulation," J. Neural Eng., 4, pp. 205-212 (2007).
Tsutsumi, et al., "Modulation of the myocardial redox state by vagal nerve stimulation after experimental myocardial infarction," Cardiovascular Research, 77, pp. 713-721 (2008).
Tyler, et al., "Chapter 17—Electrodes for the Neural Interface," Neuromodulation, Academic Press (2009).
Ulphani, et al., "Quantitative analysis of parasympathetic innervation of the porcine heart," Heart Rhythm, 7, pp. 1113-1119 (2010).
Uthman, et al., "Effectiveness of vagus nerve stimulation in epilepsy patients. A 12-year observation," Neurology, 63, pp. 1124-1126 (2004).
Van Stee, "Autonomic Innervation of the Heart," Environmental Health Perspectives, vol. 26, pp. 151-158 (1978).
Vanoli, et al., "Vagal stimulation and prevention of sudden death in conscious dogs with a healed myocardial infarction," Circulation Research, Journal of the American Heart Association, 68, pp. 1471-1481 (1991).
Vasan,. et al., "Inflammatory Markers and Risk of Heart Failure in Elderly Subjects Without Prior Myocardial Infarction," Circulation, Journal of the American Heart Association, 107, pp. 1486-1491 (2003).
Vassalle, et al., "An Analysis of Arrhythmias Induced by Ouabain in Intact Dogs," Circulation Research, Journal of the American Heart Association, 13, pp. 132-148 (1963).
Velagaleti, et al., "Long-Term Trends in the Incidence of heart Failure After Myocardial Infarction," 118, pp. 2057-2062 (2008).
Verrier, et al., "Microvolt T-Wave Alternans," Journal of the American College of Cardiology, vol. 58, No. 13, pp. 1309-1324 (2011).
Vimercati, et al., "Acute vagal stimulation attenuates cardiac metabolic response to B-adrenergic stress," The Journal of Physiology,vol. 500, No. 23, pp. 6065-6074 (2012).
Wang, et al., "Nicotinic acetylcholine receptor alpha-7 subunit is an essential regulator of inflammation," Nature, vol. 421, pp. 384-388 (Jan. 23, 2003).
Wang, et al., "Synaptic and Neurotransmitter Activation of Cardiac Vagal Neurons in the Nucleus Ambiguus," Annals New York Academy of Sciences, pp. 237-246 (2001).
Waninger, et al., "Characterization of Atrioventricular Nodal Response to Electrical Left Vagal Stimulation," Annals of Biomedical Engineering, vol. 27, pp. 758-762 (1999).
Wann, "Behavioural signs of depression and apoptosis in the limbic system following myocardial infarction: effects of sertraline," Journal of Psychopharmacology, 23(4), pp. 451-459 (2009).
Wann, et al., "Vulnerability for apoptosis in the limbic system after myocardial infarction in rats: a possible model for human postinfarct major depression," J Psychiatry Neurosci, 32(1):11-6, pp. 11-16 (2007).
Watkins, et al., "Cytokine-to-Brain Communication: A Review & Analysis of Alternative Mechanisms," Life Sciences, vol. 57, No. 11, pp. 1011-1026 (1995).
Whyte, et al., "Reactive oxygen species modulate neuronal excitability in rat intrinsic cardiac ganglia," Auton Neurosci, 150(1-2), pp. 45-52 (Oct. 5, 2009).
Yang, et al., "Sustained increases in heart rate induced by time repetition of vagal stimulation in dogs," Am. J. Physiol., 249, pp. H703-H709 (1985).
Yin, et al., "Independent prognostic value of elevated high-sensitivity C-reactive protein in chronic heart failure," American Heart Journal, vol. 147, No. 5, pp. 931-938 (2004).
Yndestad, et al., "Systemic inflammation in heart failure—the whys and wherefores," Heart Fail Rev, 11, pp. 83-92 (2006).
Yoo, et al., "High-resolution measurement of electrically-evoked vagus nerve activity in the anesthetized dog," J. Neural Eng., 10, pp. 1-9 (2013).
Yoo, et al., "Selective Control of Physiological Responses by Temporally-Patterned Electrical Stimulation of the Canine Vagus Nerve," 33rd Annual International Conference of the IEEE EMBS (2011).
Yu, et al., "Interactions between atrial electrical remodeling and autonomic remodeling: How to break the vicious cycle," Heart Rhythm, 9, pp. 804-809 (2012).
Yu, et al., "Low-level transcutaneous electrical stimulation of the auricular branch of the vagus nerve: A noninvasive approach to treat the initial phase of atrial fibrillation," Heart Rhythm, 10, pp. 428-435 (2013).
Yuan, et al., "Gross and Microscopic Anatomy of the Canine Intrinsic Cardiac Nervous System," the Anatomical Record, 239, pp. 75-87 (1994).
Yusuf, et al., "Changes in Hypertension Treatment and in Congestive Heart Failure Mortality in the United States," Hypertension, Journal of the American Heart Association, 13:I74-I179 (1989).
Zhang, et al., "Arrhythimias and vagus nerve stimulation," Heart Fail Rev, 16, pp. 147-161 (2011).
Zhang, et al., "Chronic Vagus Nerve Stimulation Improves Autonomic Control and Attenuates Systemic Inflammation and Heart Failure Progression in a Canine High-Rate Pacing Model," Journal of the American Heart Association, Circ Heart Fail, 2, pp. 692-699 (2009).
Zhang, et al., "Involvement of activated astrocyte and microglia of locus coeruleus in cardiac pain processing after acute cardiac injury," Neurol Res, 31, pp. 432-438 (2009).
Zhang, et al., "Relationship between right cervical vagus nerve stimulation and atrial fibrillation inducibility: Therapeutic intensities do not increase arrhythmogenesis,"Heart Rhythm, 6, pp. 244-260 (2009).

(56) **References Cited**

OTHER PUBLICATIONS

Zhang, et al., "Therapeutic Effects of Selective Atrioventricular Node Vagal Stimulation in Atrial Fibrillation and Heart Failure," Journal of Cardiovascular Electrophysiology, vol. 24, Issue 1, pp. 86-91 (2012).

Zheng, et al., "Vagal stimulation markedly suppresses arrhythmias in conscious rats with chronic heart failure after myocardial infarction," Proceedings of the 2005 IEEE (2005).

Zipes, et al., "Effects of selective vagal and stellate ganglion stimulation on atrial refractoriness," Cardiovascular Research, 8, pp. 647-655 (1974).

Zucker, et al., "Chronic Baroreceptor Activation Enhances Survival in Dogs with Pacing-Induced Heart Failure," Journal of the American Heart Association, Hypertension (2007).

PCT Application No. PCT/US2014/024827, Search Report and Written Opinion dated Nov. 11, 2014, 18 pages.

* cited by examiner

Fig. 1.

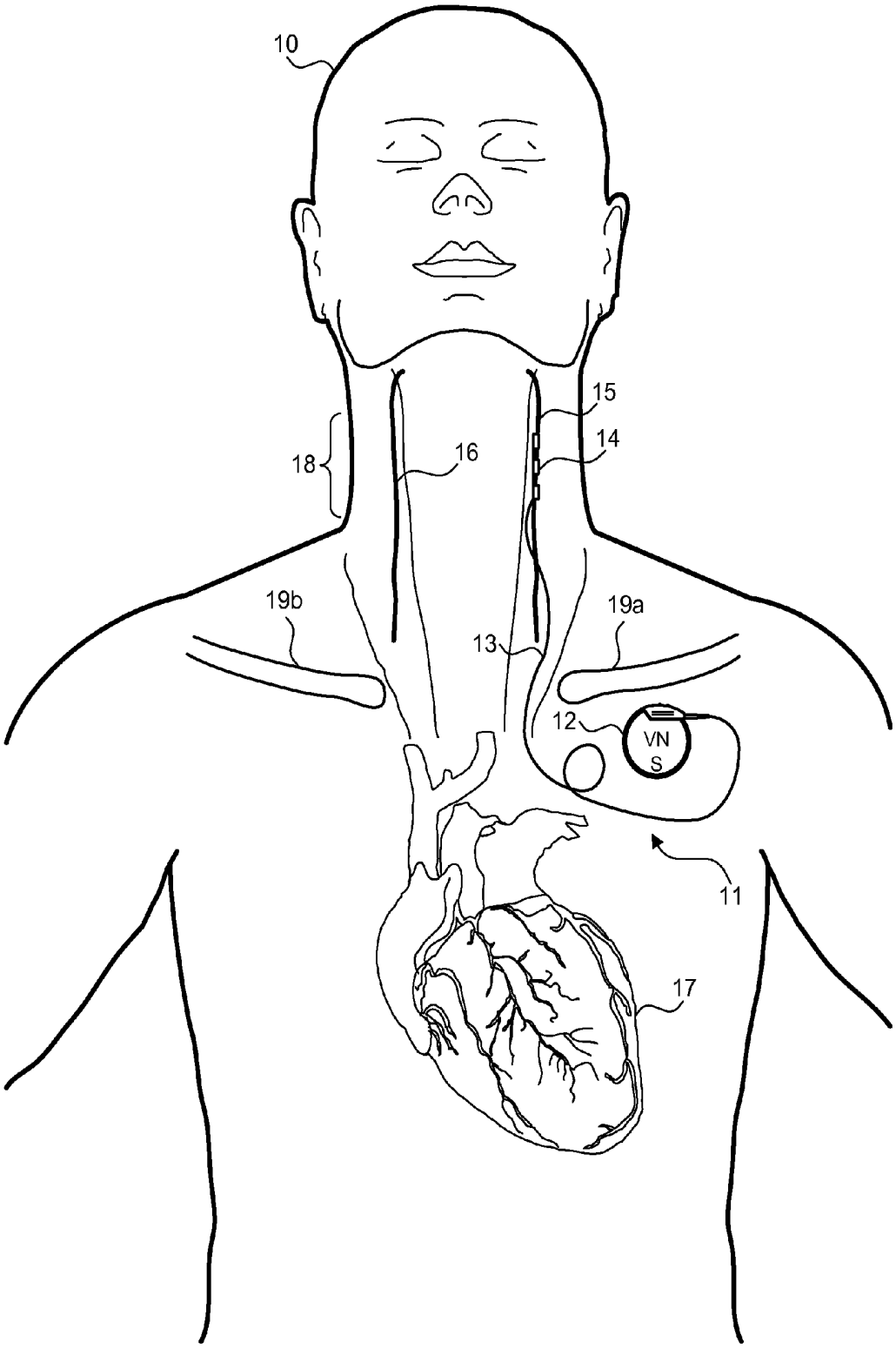


Fig. 2.

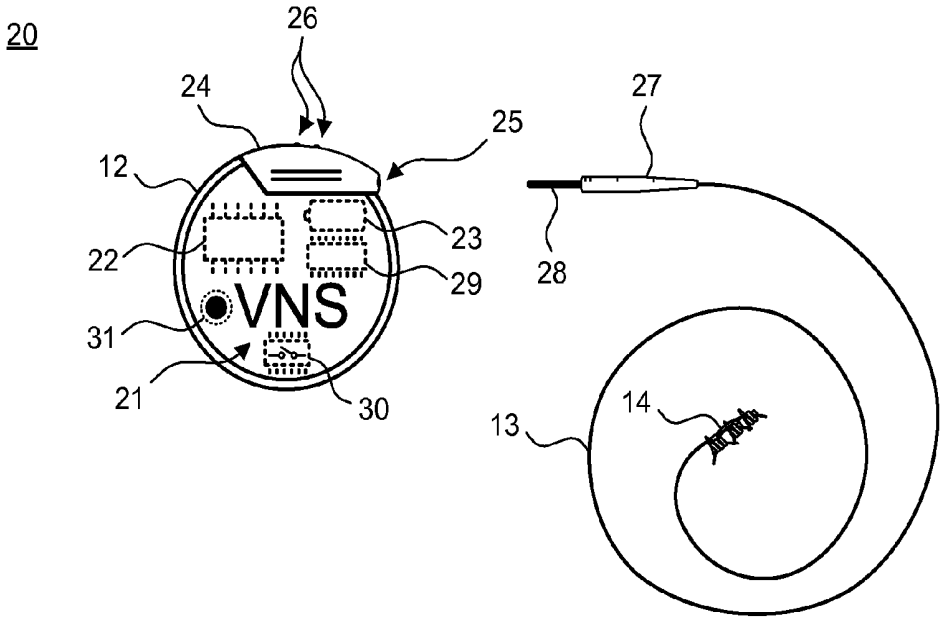

20
26
24
25
27
12
23
22
29
28
VNS
31
21
30
14
13

Fig. 3.

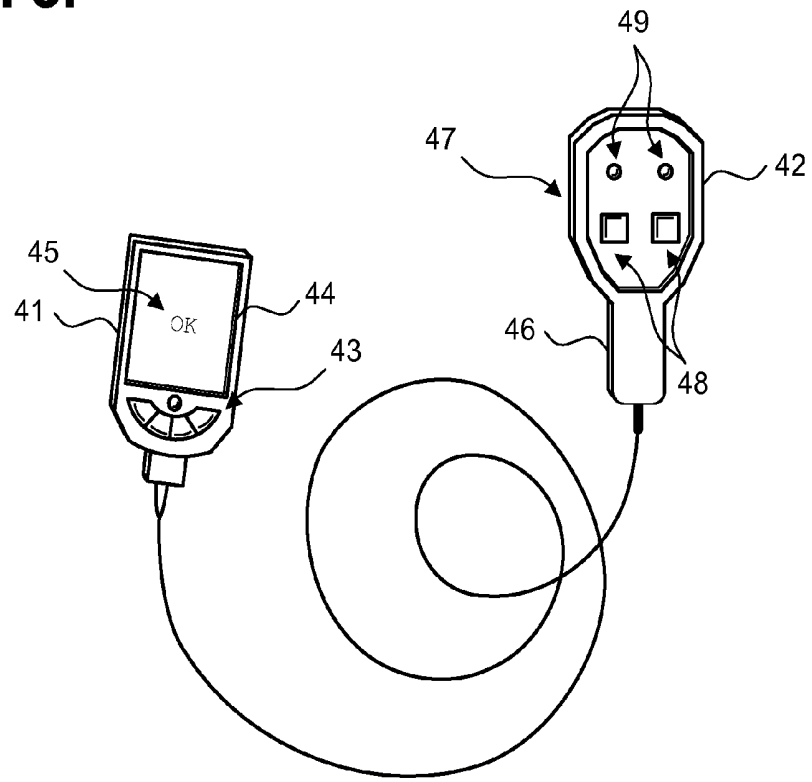

40
49
47
42
45
44
41
OK
43
46
48

Fig. 4.

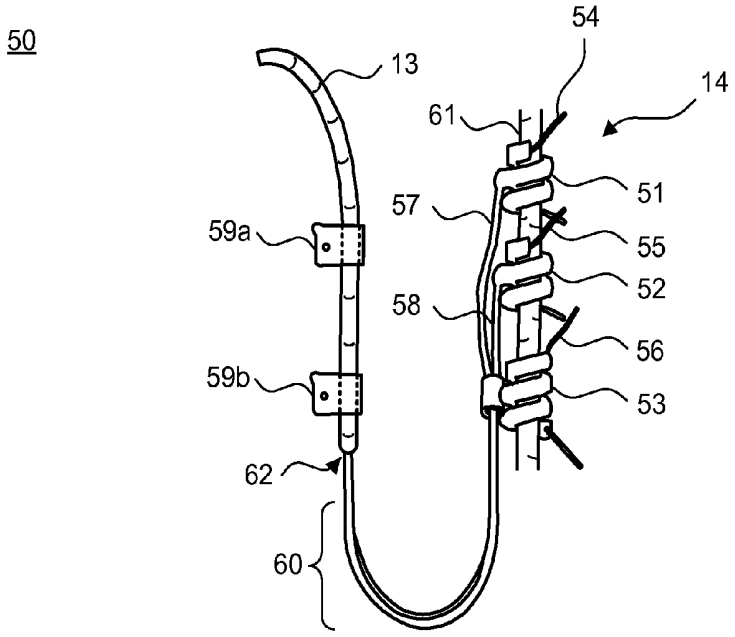

50
13
54
14
61
51
57
59a
55
52
58
56
59b
53
62
60

Fig. 5.

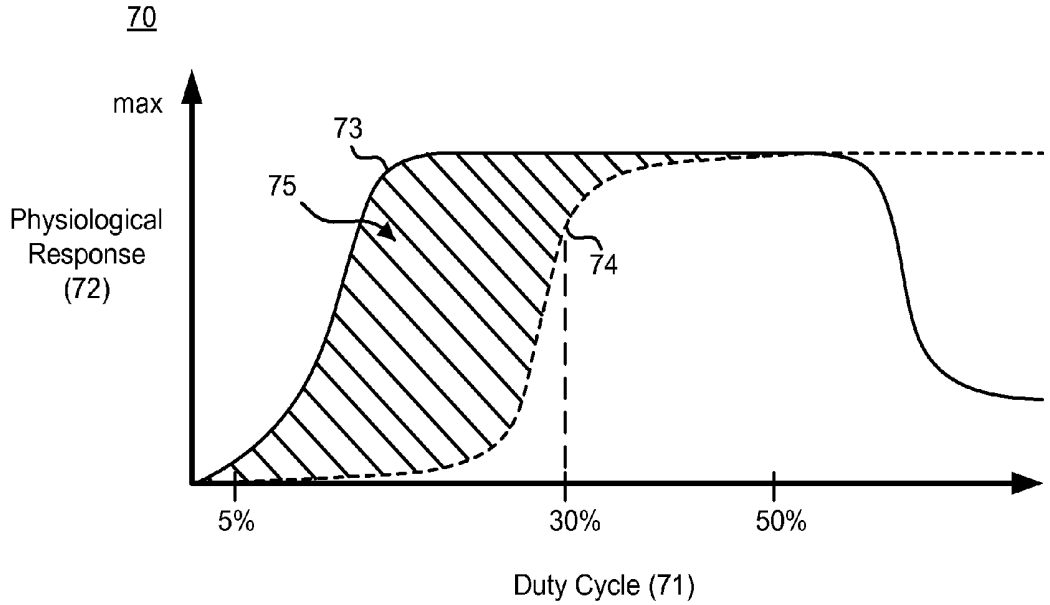

70
max
73
75
Physiological Response (72)
74
5%
30%
50%
Duty Cycle (71)

Fig. 6.

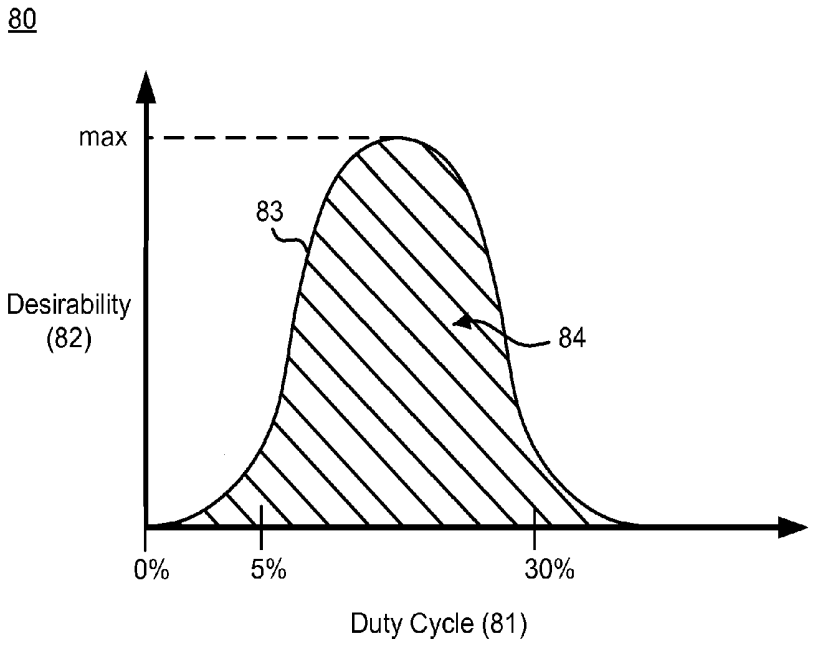
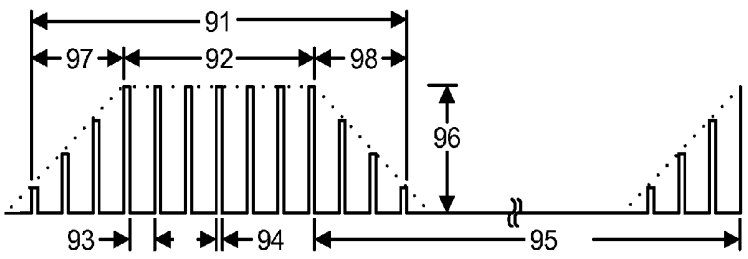

80
max
83
Desirability
(82)
84
0%
5%
30%
Duty Cycle (81)

Fig. 7.


90
91
97
92
98
96
93
94
95

IMPLANTABLE DEVICE FOR EVALUATING AUTONOMIC CARDIOVASCULAR DRIVE IN A PATIENT SUFFERING FROM CHRONIC CARDIAC DYSFUNCTION

CROSS REFERENCE TO RELATED APPLICATION

This patent application is a continuation of U.S. patent application Ser. No. 13/314,133, filed Dec. 7, 2011, now U.S. Pat. No. 8,918,190 issued Dec. 23, 2014, the priority of which is claimed and the disclosure of which is incorporated by reference in its entirety.

FIELD

This application relates in general to chronic cardiac dysfunction therapy and, in particular, to an implantable device for evaluating autonomic cardiovascular drive in a patient suffering from chronic cardiac dysfunction.

BACKGROUND OF THE INVENTION

Congestive heart failure (CHF) is a progressive and physically debilitating chronic medical condition in which the heart is unable to supply sufficient blood flow to meet the body's needs. CHF is a form of chronic cardiac dysfunction that affects nearly five million people each year in the United States alone and continues to be the leading cause of hospitalization for persons over the age of 65. CHF requires seeking timely medical attention.

Pathologically, CHF is characterized by an elevated neuroexitatory state that is accompanied by impaired arterial and cardiopulmonary baroreflex function and reduced vagal activity. CHF is initiated by cardiac dysfunction, which triggers compensatory activations of the sympathoadrenal (sympathetic) nervous and the renin-angiotensin-aldosterone hormonal systems. Initially, these two mechanisms help the heart to compensate for deteriorating pumping function. Over time, however, overdriven sympathetic activation and increased heart rate promote progressive left ventricular dysfunction and remodeling, and ultimately foretell poor long term patient outcome.

Anatomically, the heart is innervated by sympathetic and parasympathetic nerves originating through the vagus nerve and arising from the body's cervical and upper thoracic regions. The sympathetic and parasympathetic nervous systems, though separate aspects of the autonomous nervous system, dynamically interact thorough signals partially modulated by cAMP and cGMP secondary messengers. When in balance, each nervous system can presynaptically inhibit the activation of the other nervous system's nerve traffic. During CHF, however, the body suffers an autonomic imbalance of these two nervous systems, which leads to cardiac arrhythmogenesis, progressively worsening cardiac function, and eventual mortality.

Currently, the standard of care for managing chronic cardiac dysfunction, such as CHF, includes prescribing medication and mandating changes to a patient's diet and lifestyle, to counteract cardiac dysfunction. These medications include diuretics, angiotensin-converting enzyme inhibitors, angiotensin receptor blockers, beta-blockers, and aldosterone antagonists, which cause vasodilation, reduce secretion of vasopressin, reduce production and secretion of aldosterone, lower arteriolar resistance, increase venous capacity, increase cardiac output, index and volume, lower renovascular resistance, and lead to increased natriuresis, among other effects.

The effectiveness of these medications is palliative, but not curative. Moreover, patients often suffer side effects and comorbidities, such as pulmonary edema, sleep apnea, and myocardial ischemia. Re-titration of drug therapy following crisis may be required, and neither continued drug efficacy nor patient survival are assured.

More recently, cardiac resynchronization therapy (CRT) has become available to patients presenting with impairment of systolic function, such as is caused by an intraventricular conduction delay or bundle-branch block that forces the heart's ventricles to contract dyssynchronously. Typically, implantable CRT devices use a set of biventricular leads to stimulate both the ventricular septum and the lateral wall of the left ventricle. CRT restores the synchronous beating of the heart through coordinated pacing of both ventricles. However, CRT is only helpful for treating systolic dysfunction and is not indicated for patients presenting with preserved ejection fraction. Thus, CRT is limited to patients exhibiting a wide QRS complex and mechanical dyssynchrony, whereas patients presenting with systolic dysfunction or impaired ejection fraction and a narrow QRS have limited therapeutic options.

Medication and CRT are only partial solutions to managing chronic cardiac dysfunction, and neural stimulation has been proposed as an alternative way to treat chronic cardiac dysfunction conditions, such as CHF, by correcting the underlying autonomic imbalance of the sympathetic and parasympathetic nervous systems. The heart contains an intrinsic nervous system that includes spatially-distributed sensory afferent neurons, interconnecting local circuit neurons, and motor adrenergic and cholinergic efferent neurons. Peripheral cell stations of these neurons activate under the tonic influence of spinal cord and medullary reflexes and circulating catecholamines to influence overlapping regions of the heart. Suppression of excessive neural activation by electrically modulating select vagal nerve fibers may help improve the heart's mechanical function as well as to reduce the heart's intrinsic nervous system's propensity to induce atrial arrhythmias during autonomic imbalance.

Electrical vagus nerve stimulation (VNS) is currently used clinically for the treatment of drug-refractory epilepsy and depression, and is under investigation for applications in Alzheimer's disease, anxiety, heart failure, inflammatory disease, and obesity. In particular, vagus nerve stimulation has been proposed as a long-term therapy for the treatment of CHF, as described in Sabbah et al., "Vagus Nerve Stimulation in Experimental Heart Failure," Heart Fail. Rev., 16:171-178 (2011), the disclosure of which is incorporated by reference. The Sabbah paper discusses canine studies using a vagus stimulation device, manufactured by BioControl Medical Ltd., Yehud, Israel, which includes a signal generator, right ventricular sensing lead, and right vagus nerve cuff stimulation lead. The sensing leads enable stimulation of the right vagus nerve to be synchronized to the cardiac cycle through feedback on-demand heart rate control. A bipolar nerve cuff electrode was surgically implanted on the right vagus nerve at the mid-cervical position. Electrical stimulation to the right cervical vagus nerve was delivered only when heart rate increased beyond a preset level to reduce basal heart rate by ten percent. Self-titration using "magnet mode" was impracticable in light of the test subject, here canine Stimulation was provided at an impulse rate and intensity intended to keep the heart rate within a desired range by preferential stimulation of efferent nerve fibers leading to the heart while blocking afferent neural impulses to the brain. An asymmetric bi-polar multi-contact cuff electrode was employed to provide cathodic induction of action potentials while simultaneously

applying asymmetric anodal blocks that were expected to lead to preferential, but not exclusive, activation of vagal efferent fibers. Although effective in restoring baroreflex sensitivity and, in the canine model, significantly increasing left ventricular ejection fraction and decreasing left ventricular end diastolic and end systolic volumes, restoration of autonomic balance was left unaddressed.

Other uses of electrical nerve stimulation for therapeutic treatment of various physiological conditions are described. For instance, U.S. Pat. No. 6,600,954, issued Jul. 29, 2003 to Cohen et al. discloses a method and apparatus for selective control of nerve fibers. At least one electrode device is applied to a nerve bundle capable, upon activation, of generating unidirectional action potentials to be propagated through both small diameter and large diameter sensory fibers in the nerve bundle, and away from the central nervous system. The device is particularly useful for reducing pain sensations, such as propagating through the legs and arms.

U.S. Pat. No. 6,684,105, issued Jan. 27, 2004 to Cohen et al. discloses an apparatus for treatment of disorders by unidirectional nerve stimulation. An apparatus for treating a specific condition includes a set of one or more electrode devices that are applied to selected sites of the central or peripheral nervous system of the patient. For some applications, a signal is applied to a nerve, such as the vagus nerve, to stimulate efferent fibers and treat motility disorders, or to a portion of the vagus nerve innervating the stomach to produce a sensation of satiety or hunger. For other applications, a signal is applied to the vagus nerve to modulate electrical activity in the brain and rouse a comatose patient, or to treat epilepsy and involuntary movement disorders.

U.S. Pat. No. 7,123,961, issued Oct. 17, 2006 to Kroll et al. discloses stimulation of autonomic nerves. An autonomic nerve is stimulated to affect cardiac function using a stimulation device in electrical communication with the heart by way of three leads suitable for delivering multi-chamber stimulation and shock therapy. In addition, the device includes a fourth lead having three electrodes positioned in or near the heart, or near an autonomic nerve remote from the heart. Power is delivered to the electrodes at a set power level. The power is delivered at a reduced level if cardiac function was affected.

U.S. Pat. No. 7,225,017, issued May 29, 2007 to Shelchuk discloses terminating ventricular tachycardia. Cardioversion stimulation is delivered upon detecting a ventricular tachycardia. A stimulation pulse is delivered to a lead having one or more electrodes positioned proximate to a parasympathetic pathway. Optionally, the stimulation pulse is delivered post inspiration or during a refractory period to cause a release of acetylcholine.

U.S. Pat. No. 7,277,761, issued Oct. 2, 2007 to Shelchuk discloses vagal stimulation for improving cardiac function in heart failure or CHF patients. An autonomic nerve is stimulated to affect cardiac function using a stimulation device in electrical communication with the heart by way of three leads suitable for delivering multi-chamber stimulation and shock therapy. In addition, the device includes a fourth lead having three electrodes positioned in or near the heart, or near an autonomic nerve remote from the heart. A need for increased cardiac output is detected and a stimulation pulse is delivered through an electrode, for example, proximate to the left vagosympathetic trunk or branch to thereby stimulate a parasympathetic nerve. If the stimulation has caused sufficient increase in cardiac output, ventricular pacing may then be initiated at an appropriate reduced rate.

U.S. Pat. No. 7,295,881, issued Nov. 13, 2007 to Cohen et al. discloses nerve branch-specific action potential activation, inhibition and monitoring. Two preferably unidirectional electrode configurations flank a nerve junction from which a preselected nerve branch issues, proximally and distally to the junction, with respect to the brain. Selective nerve branch stimulation can be used in conjunction with nerve-branch specific stimulation to achieve selective stimulation of a specific range of fiber diameters, substantially restricted to a preselected nerve branch, including heart rate control, where activating only the vagal B nerve fibers in the heart, and not vagal A nerve fibers that innervate other muscles, can be desirous.

U.S. Pat. No. 7,778,703, issued Aug. 17, 2010 to Gross et al. discloses selective nerve fiber stimulation for treating heart conditions. An electrode device is adapted to be coupled to a vagus nerve of a subject and a control unit drives the electrode device by applying to the vagus nerve a stimulating current and also an inhibiting current, which are capable of respectively inducing action potentials in a therapeutic direction in a first set and a second set of nerve fibers in the vagus nerve and inhibiting action potentials in the therapeutic direction in the second set of nerve fibers only. The nerve fibers in the second set have larger diameters than the nerve fibers in the first set. The control unit typically drives the electrode device to apply signals to the vagus nerve to induce the propagation of efferent action potentials towards the heart and suppress artificially-induced afferent action potentials toward the brain.

U.S. Pat. No. 7,813,805, issued Oct. 12, 2010 to Farazi and U.S. Pat. No. 7,869,869, issued Jan. 11, 2011 to Farazi both disclose subcardiac threshold vagal nerve stimulation. A vagal nerve stimulator is configured to generate electrical pulses below a cardiac threshold of the heart, which are transmitted to a vagal nerve, so as to inhibit or reduce injury resulting from ischemia. The cardiac threshold is a threshold for energy delivered to the heart above which there is a slowing of the heart rate or conduction velocity. In operation, the vagal nerve stimulator generates the electrical pulses below the cardiac threshold, such that heart rate is not affected.

Finally, U.S. Pat. No. 7,885,709, issued Feb. 8, 2011 to Ben-David discloses nerve stimulation for treating disorders. A control unit can be configured to drive an electrode device to stimulate the vagus nerve, so as to modify heart rate variability, or to reduce heart rate, by suppressing the adrenergic (sympathetic) system. The vagal stimulation reduces the release of catecholamines in the heart, thereby lowering adrenergic tone at its source. For some applications, the control unit synchronizes the stimulation with the subject's cardiac cycle, while for other applications, the stimulation can be applied, for example, in a series of pulses. To reduce heart rate, stimulation is applied using a target heart rate lower than the subject's normal average heart rate.

Accordingly, a need remains for an approach to therapeutically treating chronic cardiac dysfunction, including CHF, through a form of electrical stimulation of the cervical vagus nerve to confirm pre-therapeutic cardiovascular drive and subsequently restore autonomic balance.

SUMMARY OF THE INVENTION

Excessive sustained activation of the sympathetic nervous system has a deleterious effect on long term cardiac performance and ultimately on the survival of chronic cardiac dysfunction patients. Bi-directional afferent and efferent neural stimulation through the vagus nerve can beneficially restore autonomic balance and improve long term patient outcome. Stimulus delivery can be provided through a vagal neurostimulator per a schedule specified in stored stimulation

parameters or based on sensory-based therapy triggers provided through an integrated heart rate sensor.

One embodiment provides a vagus nerve neurostimulator for evaluating autonomic cardiovascular drive. An implantable neurostimulator includes a pulse generator configured to drive electrical therapeutic stimulation tuned to restore autonomic balance through electrical pulses continuously and periodically delivered in both afferent and efferent directions of the cervical vagus nerve through a pair of helical electrodes via an electrically coupled nerve stimulation therapy lead. The implantable neurostimulator also includes a leadless heart rate sensor configured to continually monitor heart rate against a stored baseline heart rate.

A further embodiment provides an implantable device for evaluating autonomic cardiovascular drive. An implantable neurostimulator device includes a pulse generator configured to deliver both afferent and efferent therapeutic electrical stimulation to a cervical vagus nerve in continuous alternating cycles of stimuli application and stimuli inhibition. A cervical vagus nerve stimulation therapy lead is electrically coupled to the pulse generator and is terminated by a pair of helical electrodes through which the therapeutic electrical stimulation is delivered to the cervical vagus nerve. An integrated leadless heart rate sensor configured to continually monitor heart rate against a baseline heart rate stored in a memory in the pulse generator.

A still further embodiment provides an implantable device for evaluating autonomic cardiovascular drive in a patient suffering from chronic cardiac dysfunction. A cervical vagus nerve stimulation therapy lead includes a pair of helical electrodes configured to conform to an outer diameter of a cervical vagus nerve sheath of a patient and a set of connector pins electrically connected to the helical electrodes by an insulated electrical lead body. A neurostimulator is powered by a primary battery and enclosed in a hermetically sealed housing. The neurostimulator includes an electrical receptacle included on an outer surface of the housing into which the connector pins are securely and electrically coupled. The neurostimulator also includes a pulse generator configured to therapeutically stimulate the cervical vagus nerve through the helical electrodes in alternating cycles of stimuli application and stimuli inhibition that are tuned to both efferently activate the heart's intrinsic nervous system and afferently activate the patient's central reflexes by triggering bi-directional action potentials. The neurostimulator further includes a recordable memory within which is stored a baseline heart rate for the patient prior to stimulation therapy initiation. Finally, the neurostimulator includes an integrated leadless heart rate sensor configured to continually monitor the patient's heart rate in light of the baseline heart rate.

By restoring autonomic balance, therapeutic VNS operates acutely to decrease heart rate, increase heart rate variability and coronary flow, reduce cardiac workload through vasodilation, and improve left ventricular relaxation. Over the long term, VNS provides the chronic benefits of decreased negative cytokine production, increased baroreflex sensitivity, increased respiratory gas exchange efficiency, favorable gene expression, renin-angiotensin-aldosterone system down-regulation, and anti-arrhythmic, anti-apoptotic, and ectopy-reducing anti-inflammatory effects.

Still other embodiments of the present invention will become readily apparent to those skilled in the art from the following detailed description, wherein are described embodiments by way of illustrating the best mode contemplated for carrying out the invention. As will be realized, the invention is capable of other and different embodiments and its several details are capable of modifications in various obvious respects, all without departing from the spirit and the scope of the present invention. Accordingly, the drawings and detailed description are to be regarded as illustrative in nature and not as restrictive.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a front anatomical diagram showing, by way of example, placement of an implantable vagus stimulation device in a male patient, in accordance with one embodiment.

FIG. **2** is a diagram showing the implantable neurostimulator and stimulation therapy lead of FIG. **1** with the therapy lead unplugged.

FIG. **3** is a diagram showing an external programmer for use with the implantable neurostimulator of FIG. **1**.

FIG. **4** is a diagram showing the helical electrodes provided as on the stimulation therapy lead of FIG. **2** in place on a vagus nerve in situ.

FIG. **5** is a graph showing, by way of example, the relationship between the targeted therapeutic efficacy and the extent of potential side effects resulting from use of the implantable neurostimulator of FIG. **1**.

FIG. **6** is a graph showing, by way of example, the optimal duty cycle range based on the intersection depicted in FIG. **5**.

FIG. **7** is a timing diagram showing, by way of example, a stimulation cycle and an inhibition cycle of VNS as provided by implantable neurostimulator of FIG. **1**.

DETAILED DESCRIPTION OF THE INVENTION

The sympathetic nervous system affects cardiovascular physiology in an "all-or-nothing" form of neurological response, whereas the parasympathetic nervous system selectively modulates specific regions of the heart at various levels of activation. Through these two nervous systems, the autonomic nervous system directly controls the heart by affecting conduction, refractoriness, impulse formation, and the electrophysiological properties of the cardiac tissue, and indirectly by influencing the heart's homodynamics, blood flow, and metabolism, as well as exercising control over other body functions that rely on the heart.

The sympathetic and parasympathetic nervous systems dynamically interact thorough signals partially modulated by cAMP and cGMP secondary messengers to presynaptically influence the activation of each other's nerve traffic. Changes to one nervous system can indirectly affect nerve activation in the other. For instance, during autonomic imbalance, sympathetic neural activity increases while cardiac vagal activation, and therefore sympathetic innervation, is withdrawn. In view of their collaborative influence over cardiac function, the restoration of autonomic balance between these nervous systems is crucial to managing chronic cardiac dysfunction.

Conventional therapeutic alteration of cardiac vagal efferent activation through electrical stimulation of sympathetic vagal nerve fibers can produce beneficial bradycardia and modification in atrial and ventricular contractile function. However, such targeting of only the efferent nerves of the sympathetic nervous system is clinically insufficient to restore autonomic balance, as any affect on parasympathetic activation merely occurs due to incidental recruitment of parasympathetic nerve fibers. In contrast, propagating bi-directional action potentials through parasympathetic afferent and efferent nerve fibers in the vagus nerve resulting from neural stimulation engages both medullary and cardiac reflex control components and works to directly restore autonomic balance by engaging both components of both nervous systems. Moreover, many of the conventional approaches to

VNS monitor heart rate through an intracardiac lead, typically implanted into the right ventricle and adapted from sensing leads used in pacemakers and defibrillators. Implantation of these leads is surgically complex and increases risk of injury to the patient and post-surgical complications.

An implantable vagus nerve stimulator with integrated heart rate sensor, such as used to treat drug-refractory epilepsy and depression, can be adapted to use in managing chronic cardiac dysfunction through therapeutic bi-directional vagal stimulation. In addition, an integrated heart rate sensor can allow the patient's heart rate to be determined prior to the initiation of therapy delivery, or the heart rate can be provided to the stimulator from an external source. FIG. **1** is a front anatomical diagram showing, by way of example, placement of an implantable vagus stimulation device **11** in a male patient **10**, in accordance with one embodiment. The VNS provided through the stimulation device **11** operates under several mechanisms of action. These mechanisms include increasing parasympathetic outflow and inhibiting sympathetic effects by blocking norepinephrine release. More importantly, VNS triggers the release of acetylcholine (ACh) into the synaptic cleft, which has beneficial anti-arrhythmic, anti-apoptotic, and ectopy-reducing anti-inflammatory effects.

The implantable vagus stimulation device **11** includes three main components, an implantable neurostimulator **12**, a therapy lead **13**, and helical electrodes **14**. In addition, the operation of the neurostimulator **12** can be remotely checked, downloaded, diagnosed, and programmed by healthcare professionals using an external programmer (as further described below with reference to FIG. **3**). Together, the implantable vagus stimulation device **11** and the external programmer form a VNS therapeutic delivery system.

The neurostimulator **12** is implanted in the patient's right or left pectoral region generally on the same side of the patient's body as the vagus nerve **15**, **16** to be stimulated. A subcutaneous pocket is formed in the subclavicular region into which the neurostimulator **12** is placed. The helical electrodes **14** are generally implanted on the vagus nerve **15**, **16** about halfway between the clavicle **19***a-b* and the mastoid process. The therapy lead **13** and helical electrodes **14** are implanted by first exposing the carotid sheath and chosen vagus nerve **15**, **16** through a latero-cervical incision on the ipsilateral side of the patient's neck **18**. The helical electrodes **14** are then placed onto the exposed nerve sheath and tethered. A subcutaneous tunnel is formed between the respective implantation sites of the neurostimulator **12** and helical electrodes **14**, through which the therapy lead **13** is guided to the neurostimulator **12** and securely connected.

Anatomically, the vagus nerve includes a pair of nerve fiber bundles **15**, **16** that both proceed laterally through the neck, thorax, and abdomen, and distally innervate the heart **17** and other major organs and body tissue. The stimulation device **11** bi-directionally stimulates the vagus nerve **15**, **16** through application of continuous, periodic electrical stimuli. Both sympathetic and parasympathetic nerve fibers are stimulated through the helical electrodes **14** of the stimulation device **11**. Stimulation of the cervical vagus nerve results in propagation of action potentials in both afferent and efferent directions from the site of stimulation. Afferent action potentials propagate toward the parasympathetic nervous system's origin in the medulla in the nucleus ambiguus, nucleus tractus solitarius, and the dorsal motor nucleus, as well as towards the sympathetic nervous system's origin in the intermediolateral cell column of the spinal cord.

Efferent action potentials propagate toward the heart to innervate the components of the heart's intrinsic nervous system. Intracardially, the cardiac nervous system is conceived as two major outflow branches exerting reciprocal control over cardiac indices under sole influence of central neuronal command. The outflow branches respectively regulate adrenergic (sympathetic) and cholinergic (parasympathetic) efferent preganglionic neuronal activity. Innervation of the heart **17** is regionalized and exhibits a high degree of asymmetry. Within the heart **17**, the greatest concentration of vagal nerves is found first in the sinus node and then in the atrioventricular node. Cardiac efferents of the left vagus nerve **15** regulate cardiac contractility through their influence on conduction in the atrioventricular (AV) node. Cardiac efferents of the right vagus nerve **16** affect sinus node automaticity and regulate heart rate. Thus, right-sided cervical vagal stimulation tends to produce sinus bradycardia, whereas left-sided cervical vagal stimulation tends to produce AV nodal blockage.

Either the left or right vagus nerve **15**, **16** can be stimulated by the stimulation device **11**, although stimulation of the left vagus nerve **15** is preferred because stimulation of the left vagus nerve **15** is less likely to be arrhythmogenic. The left vagus nerve **15** has fewer projections to the sinoatrial node and is therefore less likely to severely reduce heart rate. Left VNS increases AV nodal conduction time and refractory period. In current form, VNS elicits bi-directional activation of both afferent and efferent nerve fibers. The balance between achieving therapeutic benefits (afferent) and side-effects (efferent) is largely determined by the threshold differences between activation of the different vagus nerve fibers.

The VNS therapy is autonomously delivered to the patient's vagus nerve **15**, **16** through three implanted components, a neurostimulator **12**, therapy lead **13**, and helical electrodes **14**. FIG. **2** is a diagram showing the implantable neurostimulator **12** and stimulation therapy lead **13** of FIG. **1** with the therapy lead unplugged **20**. In one embodiment, the neurostimulator **12** can be adapted from a VNS Therapy AspireSR Model 106 generator, manufactured and sold by Cyberonics, Inc., Houston, Tex., although other manufactures and types of single-pin receptacle implantable VNS neurostimulators with integrated leadless heart rate sensors could also be used. The stimulation therapy lead **13** and helical electrodes **14** are generally fabricated as a combined assembly and can be adapted from a Model 302 lead, PerenniaDURA Model 303 lead, or PerenniaFLEX Model 304 lead, all of which are also manufactured and sold by Cyberonics, Inc., in two sizes based on helical electrode inner diameter, although other manufactures and types of single-pin receptacle-compatible therapy leads and electrodes could also be used.

The neurostimulator **12** provides continuous alternating ON-OFF cycles of vagal stimulation that when applied to the vagus nerve through the electrodes **14**, produce action potentials in the underlying nerves that propagate bi-directionally; afferently propagating action potentials activate the medial medullary sites responsible for central reflex control and efferently propagating action potentials activate the heart's intrinsic nervous system. Cardiac motor neurons, when activated, influence heart rate, AV nodal conduction, and atrial and ventricular inotropy, thereby providing chronic cardiac dysfunction therapeutic effects. In addition, the alternating cycles can be tuned to activate phasic parasympathetic response in the vagus nerve **15**, **16** being stimulated by bi-directionally modulating vagal tone.

The neurostimulator **12** includes an electrical pulse generator that drives electrical therapeutic stimulation, which is tuned to restore autonomic balance, through electrical pulses

that are continuously and periodically delivered in both afferent and efferent directions of the vagus nerve **15**, **16**. The neurostimulator **12** is enclosed in a hermetically sealed housing **21** constructed of a biocompatible, implantation-safe material, such as titanium. The housing **21** contains electronic circuitry **22** powered by a primary battery **23**, such as a lithium carbon monoflouride battery. The electronic circuitry **22** is implemented using complementary metal oxide semiconductor integrated circuits that include a microprocessor that executes a control program according to the stored stimulation parameters as programmed into the neurostimulator **12**; a voltage regulator that regulates system power; logic and control circuitry, including a recordable memory **29** within which the stimulation parameters are stored, that controls overall pulse generator function, receives and implements programming commands from the external programmer, or other external source, and collects and stores telemetry information, processes sensory input, and controls scheduled and sensory-based therapy outputs; a transceiver that remotely communicates with the external programmer using radio frequency signals; an antenna, which receives programming instructions and transmits the telemetry information to the external programmer; and a reed switch **30** that provides a manually-actuatable mechanism to place the neurostimulator into an on-demand stimulation mode or to inhibit stimulation, also known as "magnet mode." Other electronic circuitry and components, such as an integrated heart rate sensor, are possible.

The neurostimulator **12** delivers VNS under control of the electronic circuitry **22**, particularly the logic and control circuitry, which control stimulus delivery per a schedule specified in the stored stimulation parameters, based on sensory-based therapy triggers (as further described infra) or on-demand in response to magnet mode, a programming wand instruction, or other external source. The stored stimulation parameters are programmable (as further described below with reference to FIG. **7**). In addition, sets of preselected stimulation parameters can be provided to physicians through the external programmer and fine-tuned to a patient's physiological requirements prior to being programmed into the neurostimulator **12**, such as described in commonly-assigned U.S. Pat. No. 8,630,709, entitled "Computer-Implemented System and Method for Selecting Therapy Profiles of Electrical Stimulation of Cervical Vagus Nerves for Treatment of Chronic Cardiac Dysfunction," Ser. No. 13/314,138, filed on Dec. 7, 2011, the disclosure of which is incorporated by reference. The magnet mode can be used by the patient **10** to exercise on-demand manual control over the therapy delivery and titration of the neurostimulator, such as described in commonly-assigned U.S. Pat. No. 8,600,505, entitled "Implantable Device for Facilitating Control of Electrical Stimulation of Cervical Vagus Nerves for Treatment of Chronic Cardiac Dysfunction," Ser. No. 13/314,130, filed on Dec. 7, 2011, the disclosure of which is incorporated by reference. The stimulation parameters also include the levels of stimulation for the bi-directional action potentials.

Externally, the neurostimulator **12** includes a header **24** to securely receive and connect to the therapy lead **13**. In one embodiment, the header **24** encloses a receptacle **25** into which a single pin for the therapy lead **13** can be received, although two or more receptacles could also be provided, along with the requisite additional electronic circuitry **22**. The header **24** internally includes a lead connector block (not shown) and a set of set screws **26**.

The therapy lead **13** delivers an electrical signal from the neurostimulator **12** to the vagus nerve **15**, **16** via the helical electrodes **14**. On a proximal end, the therapy lead **13** has a lead connector **27** that transitions an insulated electrical lead body to a metal connector pin **28**. During implantation, the connector pin **28** is guided through the receptacle **25** into the header **24** and securely fastened in place using the set screws **26** to electrically couple the therapy lead **13** to the neurostimulator **12**. On a distal end, the therapy lead **13** terminates with the helical electrode **14**, which bifurcates into a pair of anodic and cathodic electrodes **62** (as further described below with reference to FIG. **4**). In one embodiment, the lead connector **27** is manufactured using silicone and the connector pin **28** is made of stainless steel, although other suitable materials could be used, as well. The insulated lead body **13** utilizes a silicone-insulated alloy conductor material.

The housing **21** also contains a heart rate sensor **31** that is electrically interfaced with the logic and control circuitry, which receives the patient's sensed heart rate as sensory inputs. The heart rate sensor **31** monitors heart rate using an ECG-type electrode. Through the electrode, the patient's heart beat can be sensed by detecting ventricular depolarization. In a further embodiment, a plurality of electrodes can be used to sense voltage differentials between electrode pairs, which can be signal processed and combined into other cardiac physiological measures, for instance, P, QRS and T complexes. These cardiac artifacts can be used to derive other physiological measures and diagnose abnormal rhythm disorders and indicia, including sleep apnea, hypopnea index, dysautonomias (postural orthostatic tachycardia syndrome (POTS), vasovagal syncope, inappropriate sinus tachycardia (IST), and the like), and arrhythmia detection (atrial fibrillation, ventricular tachycardia, ventricular fibrillation, heart block, and so forth). Other direct and indirect uses of the heart rate sensor **31** are possible. In one embodiment, the heart rate sensor **31** can be adjusted for sensitivity and is capable of detecting heart beats in the range of 20 to 240 bpm. Other levels and ranges of heart beat sensitivity are possible.

Prior to the initiation of titration and eventual therapeutic stimulation, the neurostimulator **12** remains idle, yet the time period between implantation and therapy initiation provides an opportunity to passively monitor the patient's heart rate or other physiology, depending upon the capabilities of the neurostimulator **12**. Ordinarily, the heart rate sensor **31** provides the sensed heart rate to the control and logic circuitry as sensory inputs, which can be stored as data in the recordable memory **29**. When sensed prior to therapy initiation, the sensory inputs of the heart rate sensor **31** can be used as a baseline heart rate, which reflects the pre-therapeutic condition of the patient's cardiovascular drive. The sensed heart rate can be chosen as either a direct measurement of heart rate, or statistically by taking an average, minimum, maximum, or mean heart rate over time. Other ways of determining a baseline heart rate through use of the heart rate sensor **31** or other sensory-input sources or devices integrated into the neurostimulator **12** are possible.

Once therapy has begun, the sensory inputs of the heart rate sensor **31** serve as sensory-based therapy triggers to autonomously titrate VNS delivery in light of the baseline heart rate. The logic and control circuitry can then determine whether the stimulation needs to be adjusted or inhibited. Alternatively, the baseline heart rate can be programmed into the neurostimulator **12** using, for instance, an external programmer. Importantly, the baseline heart rate need not necessarily be based on the patient's heart rate per se; non-heart rate ECG measurements, for example, could be used to derive the baseline heart rate and then programmed into the neurostimulator **12**. Other ways of determining a baseline heart rate from a source outside of the neurostimulator **12** are possible.

Therapy can be adjusted whenever the sensed heart rate falls out of bounds relative to the baseline heart rate, such as outside of a predetermined heart rate range. A lower bound, stored in the recordable memory **29**, can be set to indicate bradycardia or an asystolic heart condition. The lower bound can be expressed as a ratio, percentile, or function, of the baseline heart rate, or as discrete independent (absolute) values with respect to the baseline heart rate. If the heart rate sensed by the heart rate sensor **31** falls below the lower bound on the baseline heart rate, the neurostimulator **12** can be instructed, through the stimulation parameters, to suspend the triggering of the bi-directional action potentials altogether. Therapy can also be programmed to resume automatically after a fixed time period. Alternatively, the neurostimulator **12** can be instructed to down titrate therapy by gradually adjusting the stimulation parameters downwards until the bradycardia or asystole are no longer present. Therapy can also be programmed to gradually up titrate by adjusting the stimulation parameters upwards after first inhibiting stimulation for a fixed time period. Both the down titration and the up titration can occur stepwise, where the changes in the stimulation parameters occur in small increments spread out over time, rather than all at once. VNS therapy can be titrated by adjusting the stored stimulation parameters, including output current, pulse width, and signal frequency, to different VNS therapeutic setting that are less intense (down titrate) or more intense (up titrate). An upper bound, stored in the recordable memory **29**, can also be set to indicate insufficient therapy delivery. The upper bound can be expressed as a ratio, percentile, or function, of the baseline heart rate, or as discrete independent (absolute) values with respect to the baseline heart rate. If the heart rate sensed by the heart rate sensor **31** rises above an upper bound on the baseline heart rate, the neurostimulator **12** can be instructed, again through the stimulation parameters, to up titrate the triggering of the bi-directional action potentials and thereby lower heart rate.

The neurostimulator **12** is preferably interrogated prior to implantation and throughout the therapeutic period for checking proper operation, downloading recorded data, diagnosing problems, and programming operational parameters. FIG. **3** is a diagram showing an external programmer **40** for use with the implantable neurostimulator **12** of FIG. **1**. The external programmer **40** includes a healthcare provider-operable programming computer **41** and a programming wand **42**. Generally, use of the external programmer **40** is restricted to healthcare providers, while more limited manual control is provided to the patient through "magnet mode."

In one embodiment, the programming computer **41** executes application software specially designed to interrogate the neurostimulator **12**. The programming computer **41** interfaces to the programming wand **42** through a standardized wired data connection, including a serial data interface, for instance, an EIA RS-232 or USB serial port. Alternatively, the programming computer **41** and the programming wand **42** could interface wirelessly. The programming wand **42** can be adapted from a Model 201 Programming Wand, manufactured and sold by Cyberonics, Inc. Similarly, the application software can be adapted from the Model 250 Programming Software suite, licensed by Cyberonics, Inc. Other configurations and combinations of computer **41**, programming wand **42**, and application software **45** are possible.

The programming computer **41** can be implemented using a general purpose programmable computer and can be a personal computer, laptop computer, netbook computer, handheld computer, or other form of computational device. In one embodiment, the programming computer is a personal digital assistant handheld computer operating under the Pocket-PC or Windows Mobile operating systems, licensed by Microsoft Corporation, Redmond, Wash., such as the Dell Axim X5 and X50 personal data assistants, sold by Dell, Inc., Round Top, Tex., the HP Jornada personal data assistant, sold by Hewlett-Packard Company, Palo Alto, Tex.

The programming computer **41** functions through those components conventionally found in such devices, including, for instance, a central processing unit, volatile and persistent memory, touch-sensitive display, control buttons, peripheral input and output ports, and network interface. The computer **41** operates under the control of the application software **45**, which is executed as program code as a series of process or method modules or steps by the programmed computer hardware. Other assemblages or configurations of computer hardware, firmware, and software are possible.

Operationally, the programming computer **41**, when connected to a neurostimulator **12** through wireless telemetry using the programming wand **42**, can be used by a healthcare provider to remotely interrogate the neurostimulator **12** and modify stored stimulation parameters. The programming wand **42** provides data conversion between the digital data accepted by and output from the programming computer and the radio frequency signal format that is required for communication with the neurostimulator **12**.

The healthcare provider operates the programming computer **41** through a user interface that includes a set of input controls **43** and a visual display **44**, which could be touch-sensitive, upon which to monitor progress, view downloaded telemetry and recorded physiology, and review and modify programmable stimulation parameters. The telemetry can include reports on device history that provide patient identifier, implant date, model number, serial number, magnet activations, total ON time, total operating time, manufacturing date, and device settings and stimulation statistics and on device diagnostics that include patient identifier, model identifier, serial number, firmware build number, implant date, communication status, output current status, measured current delivered, lead impedance, and battery status. Other kinds of telemetry or telemetry reports are possible.

During interrogation, the programming wand **42** is held by its handle **46** and the bottom surface **47** of the programming wand **42** is placed on the patient's chest over the location of the implanted neurostimulator **12**. A set of indicator lights **49** can assist with proper positioning of the wand and a set of input controls **48** enable the programming wand **42** to be operated directly, rather than requiring the healthcare provider to awkwardly coordinate physical wand manipulation with control inputs via the programming computer **41**. The sending of programming instructions and receipt of telemetry information occur wirelessly through radio frequency signal interfacing. Other programming computer and programming wand operations are possible.

Preferably, the helical electrodes **14** are placed over the cervical vagus nerve **15**, **16** at the location below where the superior and inferior cardiac branches separate from the cervical vagus nerve. FIG. **4** is a diagram showing the helical electrodes **14** provided as on the stimulation therapy lead **13** of FIG. **2** in place on a vagus nerve **15**, **16** in situ **50**. Although described with reference to a specific manner and orientation of implantation, the specific surgical approach and implantation site selection particulars may vary, depending upon physician discretion and patient physical structure.

The helical electrodes **14** are positioned over the patient's vagus nerve **61** oriented with the end of the helical electrodes **14** facing the patient's head. At the distal end, the insulated electrical lead body **13** is bifurcated into a pair of lead bodies **57**, **58** that are connected to a pair of electrodes proper **51**, **52**.

The polarity of the electrodes **51**, **52** could be configured into a monopolar cathode, a proximal anode and a distal cathode, or a proximal cathode and a distal anode. In addition, an anchor tether **53** is fastened over the lead bodies **57**, **58** that maintains the helical electrodes' position on the vagus nerve **61** following implant. In one embodiment, the conductors of the electrodes **51**, **52** are manufactured using a platinum and iridium alloy, while the helical materials of the electrodes **51**, **52** and the anchor tether **53** are a silicone elastomer.

During surgery, the electrodes **51**, **52** and the anchor tether **53** are coiled around the vagus nerve **61** proximal to the patient's head, each with the assistance of a pair of sutures **54**, **55**, **56**, made of polyester or other suitable material, which help the surgeon to spread apart the respective helices. The lead bodies **57**, **58** of the electrodes **51**, **52** are oriented distal to the patient's head and aligned parallel to each other and to the vagus nerve **61**. A strain relief bend **60** can be formed on the distal end with the insulated electrical lead body **13** aligned parallel to the helical electrodes **14** and attached to the adjacent fascia by a plurality of tie-downs **59***a-b*.

In one embodiment, the stimulation protocol calls for a six-week titration period. During the first three-weeks, the surgical incisions are allowed to heal and no VNS therapy occurs. During the second three-weeks, the neurostimulator **12** is first turned on and operationally tested. The impulse rate and intensity of the VNS is then gradually increased every three or four days until full therapeutic levels of stimulation are achieved, or maximal patient tolerance is reached, whichever comes first. Patient tolerance can be gauged by physical discomfort or pain, as well as based on presence of known VNS side-effects, such as ataxia, coughing, hoarseness, or dyspnea.

Therapeutically, the VNS is delivered through continual alternating cycles of electrical pulses and rest (inhibition), which is specified to the neurostimulator **12** through the stored stimulation parameters. The neurostimulator **12** can operate either with or without an integrated heart rate sensor, such as respectively described in commonly-assigned U.S. Pat. No. 8,577,458, entitled "Implantable Device for Providing Electrical Stimulation of Cervical Vagus Nerves for Treatment of Chronic Cardiac Dysfunction with Leadless Heart Rate Monitoring," Ser. No. 13/314,126, filed on Dec. 7, 2011, and U.S. patent application, entitled "Implantable Device for Providing Electrical Stimulation of Cervical Vagus Nerves for Treatment of Chronic Cardiac Dysfunction," Ser. No. 13/314,119, filed on Dec. 7, 2011, pending, the disclosures of which are incorporated by reference. Additionally, where an integrated leadless heart rate sensor is available, the neurostimulator **12** can provide self-controlled titration, such as described in commonly-assigned U.S. Patent Publication No. 2013-0158617A1, entitled "Implantable Device for Providing Electrical Stimulation of Cervical Vagus Nerves for Treatment of Chronic Cardiac Dysfunction with Bounded Titration," Ser. No. 13/314,135, filed on Dec. 7, 2011, pending, the disclosure of which is incorporated by reference.

A "duty cycle" is the percentage of time that the neurostimulator **12** is stimulating, that is, the percentage of ON times. The VNS can be delivered with a periodic duty cycle in the range of around 5% to 30%. The selection of duty cycle is a tradeoff between competing medical considerations. FIG. **5** is a graph **70** showing, by way of example, the relationship between the targeted therapeutic efficacy **73** and the extent of potential side effects **74** resulting from use of the implantable neurostimulator **12** of FIG. **1**. The x-axis represents the duty cycle **71**. The duty cycle is determined by dividing the stimulation time by the sum of the ON and OFF times of the neurostimulator **12**. However, the stimulation time may also need to include ramp-up time and ramp-down time, where the stimulation frequency exceeds a minimum threshold (as further described below with reference to FIG. **7**). The y-axis represents physiological response **72** to VNS therapy. The physiological response **72** can be expressed quantitatively for a given duty cycle **71** as a function of the targeted therapeutic efficacy **73** and the extent of potential side effects **74**, as described infra. The maximum level of physiological response **72** ("max") signifies the highest point of targeted therapeutic efficacy **73** or potential side effects **74**.

Targeted therapeutic efficacy **73** and the extent of potential side effects **74** can be expressed as functions of duty cycle **71** and physiological response **72**. The targeted therapeutic efficacy **73** represents the intended effectiveness of VNS in provoking a beneficial physiological response for a given duty cycle and can be quantified by assigning values to the various acute and chronic factors that contribute to the physiological response **72** of the patient **10** due to the delivery of therapeutic VNS. Acute factors that contribute to the targeted therapeutic efficacy **73** include increase in heart rate variability and coronary flow, reduction in cardiac workload through vasodilation, and improvement in left ventricular relaxation. Chronic factors that contribute to the targeted therapeutic efficacy **73** include decreased parasympathetic activation and increased sympathetic activation, as well as decreased negative cytokine production, increased baroreflex sensitivity, increased respiratory gas exchange efficiency, favorable gene expression, renin-angiotensin-aldosterone system down-regulation, anti-arrhythmic, anti-apoptotic, and ectopy-reducing anti-inflammatory effects. These contributing factors can be combined in any manner to express the relative level of targeted therapeutic efficacy **73**, including weighting particular effects more heavily than others or applying statistical or numeric functions based directly on or derived from observed physiological changes. Empirically, targeted therapeutic efficacy **73** steeply increases beginning at around a 5% duty cycle, and levels off in a plateau near the maximum level of physiological response at around a 30% duty cycle. Thereafter, targeted therapeutic efficacy **73** begins decreasing at around a 50% duty cycle and continues in a plateau near a 25% physiological response through the maximum 100% duty cycle.

The extent of potential side effects **74** represents the occurrence of a possible physiological effect, either adverse or therapeutic, that is secondary to the benefit intended, which presents in the patient **10** in response to VNS and can be quantified by assigning values to the physiological effects presented due to the delivery of therapeutic VNS. The degree to which a patient **10** may be prone to exhibit side effects depends in large part upon the patient's condition, including degree of cardiac dysfunction, both acute and chronic, any comobidities, prior heart problems, family history, general health, and similar considerations. As well, the type and severity of a side effect is patient-dependent. For VNS in general, the more common surgical- and stimulation-related adverse side effects include infection, asystole, bradycardia, syncope, abnormal thinking, aspiration pneumonia, device site reaction, acute renal failure, nerve paralysis, hypesthesia, facial paresis, vocal cord paralysis, facial paralysis, hemidiaphragm paralysis, recurrent laryngeal injury, urinary retention, and low grade fever. The more common non-adverse side effects include hoarseness (voice alteration), increased coughing, pharyngitis, paresthesia, dyspnea, dyspepsia, nausea, and laryngismus. Less common side effects, including adverse events, include ataxia, hypesthesia, increase coughing, insomnia, muscle movement or twitching associated with stimulation, nausea, pain, paresthesia, pharyngitis, vomiting, aspiration, blood clotting, choking sensation, nerve

damage, vasculature damage, device migration or extrusion, dizziness, dysphagia, duodenal or gastric ulcer, ear pain, face flushing, facial paralysis or paresis, implant rejection, fibrous tissue formation, fluid pocket formation, hiccupping, incision site pain, irritability, laryngeal irritation, hemidiaphragm paralysis, vocal cord paralysis, muscle pain, neck pain, painful or irregular stimulation, seroma, skin or tissue reaction, stomach discomfort, tinnitus, tooth pain, unusual scarring at incision site, vagus nerve paralysis, weight change, worsening of asthma or bronchitis. These quantified physiological effects can be combined in any manner to express the relative level of extent of potential side effects **74**, including weighting particular effects more heavily than others or applying statistical or numeric functions based directly on or derived from observed physiological changes. Empirically, the extent of potential side effects **74** is initially low until around a 25% duty cycle, at which point the potential begins to steeply increase. The extent of potential side effects **74** levels off in a plateau near the maximum level of physiological response at around a 50% duty cycle through the maximum 100% duty cycle.

The intersection **75** of the targeted therapeutic efficacy **73** and the extent of potential side effects **74** represents the optimal duty cycle range for VNS. FIG. **6** is a graph **80** showing, by way of example, the optimal duty cycle range **83** based on the intersection **75** depicted in FIG. **5**. The x-axis represents the duty cycle **81** as a percentage of stimulation time over inhibition time. The y-axis represents the desirability **82** of operating the neurostimulator **12** at a given duty cycle **81**. The optimal duty range **83** is a function **84** of the intersection **74** of the targeted therapeutic efficacy **73** and the extent of potential side effects **74**. The desirability **82** can be expressed quantitatively for a given duty cycle **81** as a function of the values of the targeted therapeutic efficacy **73** and the extent of potential side effects **74** at their point of intersection in the graph **70** of FIG. **5**. The maximum level of desirability **82** ("max") signifies a tradeoff that occurs at the point of highest targeted therapeutic efficacy **73** in light of lowest potential side effects **74** and that point will typically be found within the range of a 5% to 30% duty cycle **81**. Other expressions of duty cycles and related factors are possible.

The neurostimulator **12** delivers VNS according to stored stimulation parameters, which are programmed using an external programmer **40** (shown in FIG. **3**). Each stimulation parameter can be independently programmed to define the characteristics of the cycles of therapeutic stimulation and inhibition to ensure optimal stimulation for a patient **10**. The programmable stimulation parameters affecting stimulation include output current, signal frequency, pulse width, signal ON time, signal OFF time, magnet activation (for VNS specifically triggered by "magnet mode"), "AutoStim" activation (delivered upon detection of a biological signal indicative of physiological conditions, such as bradycardia or asystole), and reset parameters. Other programmable parameters are possible.

VNS is delivered in alternating cycles of stimuli application and stimuli inhibition that are tuned to both efferently activate the heart's intrinsic nervous system and heart tissue and afferently activate the patient's central reflexes. FIG. **7** is a timing diagram showing, by way of example, a stimulation cycle and an inhibition cycle of VNS **90** as provided by implantable neurostimulator **12** of FIG. **1**. The stimulation parameters enable the electrical stimulation pulse output by the neurostimulator **12** to be varied by both amplitude (output current **96**) and duration (pulse width **94**). The number of output pulses delivered per second determines the signal frequency **93**. In one embodiment, a pulse width in the range of 100 to 250 μsec delivers between 0.02 and 50 mA of output current at a signal frequency of about 20 Hz, although other therapeutic values could be used as appropriate.

In the simplest case, the stimulation time is the time period during which the neurostimulator **12** is ON and delivering pulses of stimulation. The OFF time **95** is always the time period occurring in-between stimulation times **91** during which the neurostimulator **12** is OFF and inhibited from delivering stimulation. In one embodiment, the neurostimulator **12** implements a ramp-up time **97** and a ramp-down time **98** that respectively precede and follow the ON time **92** during which the neurostimulator **12** is ON and delivering pulses of stimulation at the full output current **96**. The ramp-up time **97** and ramp-down time **98** are used when the stimulation frequency is at least 10 Hz, although other minimum thresholds could be used, and both times last two seconds, although other time periods could also be used. The ramp-up time **97** and ramp-down time **98** allow the strength of the output current **96** of each output pulse to be gradually increased and decreased, thereby avoiding unnecessary trauma to the vagus nerve due to sudden delivery or inhibition of stimulation at full strength.

While the invention has been particularly shown and described as referenced to the embodiments thereof, those skilled in the art will understand that the foregoing and other changes in form and detail may be made therein without departing from the spirit and scope.

What is claimed is:

1. A vagus nerve neurostimulator for modulating autonomic cardiovascular drive, comprising:

a pulse generator, wherein the pulse generator generates a pulsed electrical signal comprising:

a signal ON time;

a signal OFF time;

an output current;

a signal frequency of approximately 10 Hz;

a pulse width; and

a duty cycle defined by dividing the signal ON time by the sum of the signal ON time and signal OFF time;

a therapy lead; and

an electrode communicatively coupled to the pulse generator via the therapy lead, wherein the electrical signal is applied to a vagus nerve via the electrode to propagate action potentials in both afferent and efferent directions along the vagus nerve at an intensity that avoids acute physiological side effects.

2. The vagus nerve neurostimulator according to claim **1**, wherein the pulsed electrical signal further comprises a signal ramp-up time.

3. The vagus nerve neurostimulator according to claim **1**, wherein the pulsed electrical signal further comprises a signal ramp-down time.

4. The vagus nerve neurostimulator according to claim **1**, wherein the duty cycle comprises a value in a range of 5% to 20%.

5. A vagus nerve neurostimulator for modulating autonomic cardiovascular drive, comprising:

a pulse generator, wherein the pulse generator generates a pulsed electrical signal comprising:

a signal ramp-up time;

a signal ramp-down time;

a signal ON time;

a signal OFF time;

an output current;

a signal frequency of approximately 10 Hz;

a pulse width; and

a duty cycle defined by dividing the signal ON time by the sum of the signal ON time and signal OFF time;

a therapy lead; and

an electrode communicatively coupled to the pulse generator via the therapy lead, wherein the electrical signal is applied to a vagus nerve via the electrode to propagate action potentials in both afferent and efferent directions along the vagus nerve at an intensity that avoids acute physiological side effects.

6. The vagus nerve neurostimulator according to claim **5**, wherein the signal ramp-up time is two seconds.

7. The vagus nerve neurostimulator according to claim **5**, wherein the signal ramp-down time is two seconds.

8. The vagus nerve neurostimulator according to claim **5**, wherein the output current, the signal frequency or the pulse width of the pulsed electrical signal is modified during the ramp-up time.

9. The vagus nerve neurostimulator according to claim **5**, wherein the output current, the signal frequency or the pulse width of the pulsed electrical signal is modified during the ramp-down time.

10. A vagus nerve neurostimulator for modulating autonomic cardiovascular drive, comprising:

a pulse generator, wherein the pulse generator generates a pulsed electrical signal comprising:

a signal ON time;

a signal OFF time;

an output current;

a signal frequency of approximately 10 Hz;

a pulse width; and

a duty cycle defined by dividing the signal ON time by the sum of the signal ON time and signal OFF time;

a therapy lead; and

an electrode communicatively coupled to the pulse generator via the therapy lead, wherein the electrical signal is applied to a vagus nerve via the electrode to:

propagate action potentials in both afferent and efferent directions along the vagus nerve.

11. The vagus nerve neurostimulator according to claim **10**, wherein the pulsed electrical signal further comprises a signal ramp-up time.

12. The vagus nerve neurostimulator according to claim **10**, wherein the pulsed electrical signal further comprises a signal ramp-down time.

13. The vagus nerve neurostimulator according to claim **10**, wherein the duty cycle comprises a value in a range of 5% to 20%.

* * * * *

专利名称(译)	用于评估患有慢性心脏功能障碍的患者的自主心血管驱动的可植入装置		
公开(公告)号	US9114262	公开(公告)日	2015-08-25
申请号	US14/540337	申请日	2014-11-13
申请(专利权)人(译)	Cyberonics公司，INC.		
当前申请(专利权)人(译)	Cyberonics公司，INC.		
[标]发明人	LIBBUS IMAD AMURTHUR BADRI KENKNIGHT BRUCE H		
发明人	LIBBUS, IMAD AMURTHUR, BADRI KENKNIGHT, BRUCE H.		
IPC分类号	A61N1/05 A61B5/00 A61B5/02 A61N1/36		
CPC分类号	A61N1/36167 A61B5/02 A61B5/4836 A61N1/0551 A61N1/36053 A61N1/36114 A61N1/36139 A61B5/02438 A61B5/686 A61N1/05		
助理审查员(译)	CAREY，MICHAEL		
其他公开文献	US20150073512A1		
外部链接	Espacenet USPTO		

摘要(译)

提供了一种用于评估患有慢性心脏功能障碍的患者（<b> 10 </ b>）中的自主心血管驱动的可植入装置（<b> 11 </ b>）。刺激治疗导联（<b> 13 </ b>）包括配置成符合颈部迷走神经鞘外径的螺旋电极（<b> 14 </ b>）和一组连接器针（<b> > 28 </ b>电连接到螺旋电极（<b> 14 </ b>）。神经刺激器（<b> 12 </ b>）包括电插座（<b> 25 </ b>），连接器插针（<b> 28 <b>）牢固且电耦合到该电插座中。神经刺激器（<b> 12 </ b>）还包括脉冲发生器，其配置为在刺激施加和刺激抑制的交替循环中通过螺旋电极（<b> 14 </ b>）治疗性地刺激迷走神经（<b）> 90 </ b>调整为激发心脏内在神经系统，并通过触发双向动作电位而不同地激活患者的中枢反射。神经刺激器（<b> 12 </ b>）包括存储基线心率的可记录存储器（< b> 29 </ b>）。