Ionic and pharmacological characteristics of the hyperpolarizing ACh responses and IJPs. *A* + or − indicates presence or absence of a blocking effect. *B* + or − indicates presence or absence of ionic dependence. ( ), indirect evidence

	ACh H-response	IJP
A) Mytolon	+	+
Tubocurarine	+	+
Methylxyolocholine	−	−
Hexamethonium	−	−
B) Cl^--dependence	+	+
Na^+-dependence	−	(−)

The methylxylocholine-sensitive K^+-mediated response to ionophoretic ACh application, which is found in bivalve myocardium[2], was not found in the present materials. The physiological role of the Na^+-mediated depolarizing ACh response is not yet known. Further investigation of neuronal and neurohumoral control of the myocardium may elucidate these subjects further.

Acknowledgments. We thank Dr R.B. Hill for revising this manuscript and for helpful comments. We also thank Miss Y. Fujiwara and Messrs K. Tanaka and S. Matsumura for technical assistance and for preparing the manuscript, and Mr K. Shishikura for collecting *Pleurobranchaea*. Contribution from the Shimoda Marine Research Center No. 471.

1 Elliott, E.J., Cholinergic response in the heart of the clam *Mercenaria mercenaria:* Activation by *Conus californicus* venom component. J. comp. Physiol. *129* (1979) 61–66.
2 Elliott, E.J., Three types of acetylcholine response in bivalve heart muscle cells. J. Physiol. *300* (1980) 283–302.
3a Greenberg, M.J., A comparison of acetylcholine structure-activity relations on the hearts of bivalve molluscs. Comp. Biochem. Physiol. *33* (1970) 259–294.
3b Greenberg, M.J., A compendium of responses of bivalve hearts to acetylcholine. Comp. Biochem. Physiol. *14* (1965) 513–539.
4 Hill, R.B., and Welsh, J.H., Heart, circulation, and blood cells, in: Physiology of Mollusca, vol. 2, pp. 125–174. Eds K.M. Wilbur and C.M. Yonge. Academic Press, New York 1966.
5 Hill, R.B., Effects of acetylcholine on resting and action potentials and on contractile force in the ventricle of *Dolabella auricularia*. J. exp. Biol. *61* (1974) 629–637.
6 Hill, R.B., and Yantorno, R.E., Inotropism and contracture of aplysiid ventricles as related to the action of neurohumors on resting and action potentials of molluscan hearts. Am. Zool. *19* (1979) 145–162.
7 Jaeger, C.P., Physiology of Mollusca. I. Action of acetylcholine on the heart of *Strophocheilus oblongus*. Comp. Biochem. Physiol. *4* (1961) 30–32.
8 Jones, H.D., The circulatory systems of gastropods and bivalves, in: The Mollusca, vol. 5, Physiology, Part 2, pp. 189–238. Eds A.S.M. Salenddin and K.M. Wilbur. Academic Press, New York 1983.
9 Kehoe, J.S., Ionic mechanisms of a two-component cholinergic inhibition in *Aplysia* neurones. J. Physiol. *225* (1972a) 85–114.
10 Kehoe, J.S., Three acetylcholine receptors in *Aplysia* neurones. J. Physiol. *225* (1972b) 115–146.
11 Krijgsman, B.J., and Divaris, G.A., Contractile and pacemaker mechanisms of the heart of molluscs. Biol. Rev. *30* (1955) 1–39.
12 Kuwasawa, K., Transmission of impulse from the cardiac nerve to the heart in some molluscs (*Aplysia* and *Dolabella*). Sci. Rep. Tokyo Kyoiku Daigaku B*13* (1967) 111–128.
13 Kuwasawa, K., Effects of ACh and IJPs on the AV valve and the ventricle of *Dolabella auricularia*. Am. Zool. *19* (1979) 129–143.
14 Kuwasawa, K., and Yazawa, T., Effects of tubocurarine on excitatory and inhibitory junctional potentials in the heart of *Dolabella auricularia*, in: Neurotransmitters in Invertebrates. Adv. Physiol. Sci., vol. 22, pp. 113–132. Ed. K.S.-Rózsa. Pergamon Press and Akadémiai Kiadó 1981.
15 Liebeswar, G., Goldman, J.E., Koester, J., and Mayeri, E., Neural control of circulation in *Aplysia*. III. Neurotransmitters. J. Neurophysiol. *38* (1975) 767–779.
16 Luduena, F.P., and Brown T.G. Jr, Mytolon and related compounds as antagonists of acetylcholine on the heart of *Venus mercenaria*. J. Pharmac. exp. Ther. *105* (1952) 232–239.
17 S.-Rózsa, K., and Zs.-Nagy, I., Physiological and histochemical evidence for neuroendocrine regulation of heart activity in the snail, *Lymnaea stagnalis* L. Comp. Biochem. Physiol. *23* (1967) 373–382.
18 S.-Rózsa, K., Kiss, T., and Szöke, V.-I., On the role of bioactive substances in the rhythm regulation of heart muscle cells of Gastropoda and Insecta, in: Neurobiology of Invertebrates: Mechanisms of Rhythm Regulation, pp. 167–181. Ed. J. Salanki. Akadémiai Kiadó, Budapest 1973.
19 Tauc, L., and Gerschenfeld, H.M., A cholinergic mechanism of inhibitory synaptic transmission in a molluscan nervous system. J. Neurophysiol. *25* (1973) 236–262.

0014-4754/87/090986-05$1.50 + 0.20/0

Cardiac and circulatory control in decapod Crustacea with comparisons to molluscs

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Summary. In this review I will attempt to identify the circulatory requirements a decapod is likely to encounter and how the heart is controlled to meet these demands. The decapod heart has been designed as an autonomous system endowed with an intrinsic autorhythmic pacemaker ganglion. Muscle fibers are multiply-innervated and capable of producing regenerative action potentials. This vitally important organ has been designed to be nearly fail-safe. Stroke volume is more important than heart rate in determining cardiac output. Stretch sensitivity of the cardiac ganglion and of the myocardium as well as extrinsic nervous and hormonal modulation of the heart can all contribute to changes in stroke volume. It may be advantageous to an animal to switch the circulation between various vascular beds to meet changing perfusion demands. Neuronal and hormonal mechanisms have been identified which exert differential control of the cardioarterial valves, but it is not known whether switching does occur and if so whether these valves participate in the process. Changes in peripheral resistance can also redirect circulatory flow. The circulatory and ventilatory systems demonstrate coordinated rate changes which suggest that the heart is responding to meet changing ventilatory performance requirements. This coupling is controlled both by the hydrostatic pressure pulses generated within the branchial chambers and by common higher level nervous inputs. Comparisons of the cardiovascular systems of crustaceans and molluscs, based on the papers presented at this symposium, are high-lighted.
Key words. Decapod Crustacea; cardiac control; cardiac output.

Introduction

The isolated heart, the cardiac ganglion (CG) and the regulatory nerves to the heart have received considerable research attention where the primary focus has been to understand the physiology of the particular tissue in question. Heart rate

and more rarely cardiac output of intact animals has been monitored in other studies where the main focus has usually been to examine the responses of animals to various environmentally related perturbations (oxygen tension, salinity and others) (see refs 28, 41, 46, 54, 62). In this review, I wish to change the focus slightly to ask (a) what are the circulatory requirements of a typical decapod and (b) how is the heart controlled to meet these requirements?

Circulatory requirements

Most simply stated, the heart must supply the animal with hemolymph which serves the functions of gas, nutrient, waste and hormonal transport. In fulfilling its transport functions, at least three categories of variables can be identified or anticipated: cardiac output (CO), circulatory switching and cardio-ventilatory coordination.

1) Cardiac output must change to meet changing circulatory demands as, for example, when an animal moves from rest to active locomotion. Cardiac output is defined as:

$$CO = f_H \times SV$$

where both heart rate (f_H) and stroke volume (SV) are themselves independently controllable variables. From the large number of in vitro studies it is easy to derive the impression that f_H may be the predominent variable controlled within an animal. On the other hand, a number of studies drawn primarily from the respiratory literature suggest that SV, not f_H, may be the more important variable in determining CO in situ[45, 46, 54]. This is exemplified by two studies on *Cancer magister*, the first showing that following 29 min of forced exercise CO increased by 116% (Fick principle calculations), but f_H increased by only 18%[47]. In the second study, f_H changed by less than 20% whereas SV (measured by thermodilution) varied by about 150% as crabs were subjected to progressive hypoxia and then allowed to recover[30, 45].

2) One can predict that it would be advantageous to switch circulatory flow between various vascular beds, as for example between the viscera and the skeletal musculature during resting, post-absorptive or active locomotory states. To-date, there is only suggestive evidence that the heart participates in this process[34]. Changes in the peripheral resistance to hemolymph flow, resulting in circulatory switching between the gill and branchiostegite 'lung' vascular beds, is known to occur in the bimodally breathing crab *Holthuisana transversa* as it alternates between aquatic and aerial respiration[56]. When in air, the branchial resistance to blood flow through gills increases as the gills become compressed, thereby diverting more hemolymph through the 'pulmonary' route.

3) Cardio-ventilatory coordination[4, 13, 29, 44, 55] effected by both nervous inputs and hemolymph pressure[54, 62] has been demonstrated in several species of decapods. This coordination is manifest as simultaneous cardiac arrest and apnea, bradycardia tightly coupled with periods of reversed ventilation, and slight tachycardia associated with hyperventilation. During reversed ventilatory pumping in *Carcinus maenas* the positive hydrostatic pressure generated in the branchial chambers appears to express hemolymph from the gills, increasing venous return which ultimately results in increased pericardial sinus and ventricular diastolic pressures[10]. In the land crab *Cardiosoma guanhumi*, where the scaphognathites (gill bailers) pump air, reversed ventilation likewise produced 29% increases in branchial as well as cardiac diastolic and systolic pressure[12]. A 5–10% bradycardia also occurs. Holes drilled in the branchial chambers prevented both the branchial and cardiac pressure pulses, but not the bradycardia.

Bursts of spikes are recorded from the cardio-inhibitor (CI) nerves during periods of apnea in *Nephrops norvegicus* and these bursts can be induced by stimulating the circumesophageal connectives (CC)[67]. Interneurons in the CC of *C. magister* have been identified which when stimulated simultaneously induce reversed ventilation and bradycardia and/or cardiac arrest[64].

Cardiac control: Mechanisms by which circulatory requirements can be achieved

Innervation of the myocardium

The neurogenic heart of decapods is supplied by a nine-neuron cardiac ganglion (CG) located on the inner dorsal wall of the heart. The functional organization of the CG which results in the production of bursts of action potentials in the motor neurons has received much attention[8, 15, 20, 26, 28, 39, 57, 58]. It has generally been thought that the 4 posterior small cells (SC) are the pacemakers while the 5 anterior large cells (LC), although participating in pattern generation, are the motor neurons innervating the myocardicum. Recent studies on *Panulirus japonicus* employing transections at various locations within the CG have shown that the amplitude and duration of bursts of the LC's are modified, but are not dependent, on SC activity[36].

Cardiac muscle fibers are polyneuronally innervated[3, 27, 36]. In *P. japonicus* muscle cells are activated by six or more axons as a result of the overlapping innervation by two or more of the branches leaving the CG[36]. In *Homarus americanus* synaptic activation results in summing and facilitating excitatory junction potentials (EJP)[3], while muscle fibers of *Portunus sanguinolentus* produce regenerative overshooting action potentials followed by depolarized plateaus which arise from summed EJP's[9].

As in molluscs and vertebrates, the decapod heart is functionally independent of the rest of the organism due to its autorhythmicity, but differs in being neurogenic. This system is rendered additionally reliable since the motor neurons (LC's) of the CG in at least one species are able to generate coordinated bursts of potentials when isolated from the 'pacemaker' SC's[36] and since the muscle cells in one species are capable of generating regenerative spikes[9]. Both of these features will help ensure the reliability of the heart.

Effects of stretch on cardiac output

Isolated hearts are internally perfused in order to maintain beating. Beat frequency is proportional to perfusion pressure (stretch) and can vary from as low as 10 to as high as 120 beats per min[33, 35, 41]. As pressure increases, tonus increases slightly (incomplete diastolic relaxation?) and systolic force increases. There is, however, no apparent change in magnitude of the EMG (recorded with suction electrodes) associated with the increase in contractile force. Intracellular recordings from muscle fibers will be required to determine whether stretch is affecting the contractural capability independently of membrane electrical properties. Stretch-induced changes in the length/tension relationship of muscle fibers would also be expected to influence both diastolic tonus and systolic force, but this has not been examined. Sudden drops in perfusion pressure result in a gradual decrease in amplitude of EJP's and contractile force followed by a gradual spontaneous return[35]. Each of the different sets of ganglion cells (four anterior LC's, median LC and four SC's) responds differently to stretch.

Each CG burst is terminated by accumulated refractoriness[37]; however, at low burst rates, secondary bursts and double contractions are often observed[33, 35]. The secondary bursts appear to arise from the sustained tonic firing of the SC's which feed forward to re-recruit the LC's as they recover from refractoriness. Such double contractions which

are observed in vitro and also in situ (personal observations) may facilitate effective cardiac output at low heart rates.

As in vertebrates, the decapod heart obeys the Starling Law and in intact animals the stretch sensitivity of the CG and myocardium may lead to a certain amount of autoregulation of CO. In situ the heart is not filled by a positive pressure, but rather during diastole, a slight negative pressure gradient exists between the heart lumen and the pericardial sinus. Hemolymph enters the heart relatively slowly through ostia[7, 10, 12]. During diastole the heart will be stretched by the elastic recoil of the suspensory ligaments which attach the heart to the walls of the pericardial sinus. Any excitatory drive (nervous or hormonal) which increases systolic contraction will also result in greater stretch of the suspensory ligaments, stretch sensitive neurites of ganglion cells and the muscle cells themselves.

A second source of extrinsic stretch to the heart may arise from the ligamentous connections between the pericardial septum and the ventral wall of the heart. Muscle bands are present in the pericardial septum of lobsters and crayfish[25, 38], but apparently not in crabs (personal observations). It is not known whether these muscles play any role in the circulatory process. If the muscles can depress the upwardly convex membrane, the ventral wall of the heart would also be depressed. The pericardial septum may also be depressed passively by increases in venous return to the pericardial sinus as has been observed during ventilatory reversals[10, 12]. Any depression of the membrane during diastole would serve to increase ventricular lumen volume, increase the diastolic negative pressure gradient and stretch the heart.

Cardiac output may therefore be increased by a combination of increased end diastolic volume, and decreased end systolic volume, resulting from both the mechanical organization of the heart's suspension in the pericardium and from the intrinsic properties of the cardiac tissue.

Extrinsic controls

Superimposed on the autorhythmicity and stretch sensitivity of the neurogenic heart are a variety of external controls, both neural and hormonal. Neural control of the heart is exerted by the cardio-accelerator (CA) and cardio-inhibitor (CI) nerves which originate in the central nervous system and are known to synapse on the CG. Electrical stimulation of these nerves alters frequency and force of heart beat[14, 22, 23, 40, 59, 61]. Anatomical studies have suggested that the regulatory nerves send their processes both to the main CG trunk and out to the periphery[1, 42]; however, most physiological studies have focused exclusively on synaptic connections within the main CG trunk. Recent studies on two species of hermit crabs[65, 66] have established that the CI and CA axons follow different routes within the heart. The CI's synapse within the main CG and contribute IPSP's to the large cells only. On the other hand, the CA's excite the heart multimodally: centrally within the CG, on peripheral motor processes in the circular trunks emanating from the CG, and directly on the myocardium including the ostal valves. CA-induced EPSP's on the CG produce a positive chronotropic effect, while synapses at the second and third sites are capable of increasing both the amplitude of heart contraction (positive inotropic effect) and heart tension (positive tonotropic effect) (Miyazaki et al., 1985, quoted in ref. 66).

The second extrinsic source of regulation of heart function is exerted by neurohormones. Hormones stored in, released from and in a few cases synthesized in the pericardial organs (PO), a plexus of neurosecretory neurons and terminals located in the pericardial sinus[11, 53], include acetylcholine, dopamine, 5-hydroxytryptamine (5HT), octopamine and two peptides, one of which has been identified as proctolin[2, 6, 16–18, 21, 43, 50, 53]. The responses to each of these compounds will be reviewed separately:

a) 5HT applied with the perfusate to isolated lobster and crayfish hearts causes increased frequency[5, 17, 24] and amplitude of beating[5]. cAMP levels in the lobster heart[5], but not in the CG[37], are stimulated by 5HT. When applied to the isolated CG 5HT caused increased burst rate, but no changes or slight decreases in burst duration[17, 19, 37]. The SC's are more responsive to 5HT than the LC's. Effects of 5HT on the cardiac valves will be reviewed below.

b) Dopamine stimulates increased f_H in isolated hearts[24], but the site of action has not been elucidated.

c) Octopamine causes both increased frequency and amplitude of heart beat in lobsters and crayfish[5, 24], but effective doses are greater than for 5HT. cAMP also increases in hearts exposed to octopamine[5]. See below for effects on cardiac valves.

d) The PO's contain two peptides, one of which has been identified as the penta-peptide proctolin[49, 51]. When applied to perfused hearts proctolin produces a positive inotropic, whereas the 'other' peptide produces a chronotropic effect[51]. When applied to the isolated CG, proctolin caused prolonged bursts in the SC's which can lead to double bursts from the LC motor neurons, and when applied only to the LC's caused a slowly developing depolarization and increased burst rate[48, 52]. The proctolin effects on the isolated CG appear to be opposite to those on intact hearts except at low burst rates where the double bursts would have the effect of increasing contractile force. There are no direct effects of this hormone on the myocardium[52] similar to those that as have recently been reported for *Limulus* heart[60]. The reason for this difference is not clear. The separation of these two peptides has made older studies using the crude peptide fractions of PO extracts difficult to interpret[17, 19].

In intact *C. maenas* the injection of 5HT, dopamine, octopamine or proctolin, even at high concentrations, produced only small increases in heart rate which return to control levels in less than 30 min[63]. The hearts of intact crayfish and lobsters also respond weakly to these hormones (personal observations). A more complete picture of hormone effects on intact animals requires that SV or contraction amplitude be measured as well as frequency, but these measurements have not been made.

It is not possible at this point to relate the hormonal effects at any level of the heart system to possible changes in CO. However, it seems reasonable to predict that moderate increases in burst rate, increases in number of spikes per burst, and prolonged bursts would cause neuromuscular facilitation[3] which in turn would be expected to increase SV by causing more complete systolic emptying of the heart.

Circulatory switching

Kuramoto and Ebara[34] provided evidence that the heart may be able to facultatively redirect circulatory flow to different parts of the body when they found that octopamine, 5HT and proctolin produced different effects on the cardio-arterial valve muscles in *P. japonicus*. Proctolin caused the anterior and posterior valves to depolarize and contract. 5HT produced the opposite effects, hyperpolarizing and relaxing the anterior and posterior valves, an effect which would facilitate hemolymph flow. Octopamine caused the posterior valve to contract and the anterior valve muscles to hyperpolarize and remain in a relaxed state. Valve muscle contractions may tension the valves to reduce reflux of arterial hemolymph back into the heart; however, they may also hold the valves shut and thereby reduce hemolymph flow out of the arteries so affected. Once again, it is not known whether this potential switching capability is used by decapods.

Anatomical observations indicate that the cardio-arterial

valves of decapods are innervated[1, 41], and the anterior valve receives octopamine containg neurons[34]. To-date, there have been physiological studies neither of the effects of this innervation nor of when these pathways might be utilized. The nervous control of the cardio-arterial valves in an isopod, *Bathynomus doederleini,* has been studied[31, 32]. The hemolymph flow out of individual arteries of this isopod can be regulated by the unique innervation patterns of different valves. Some valves are dually innervated by excitatory and inhibitory neurons while others are singly innervated by either excitatory or inhibitory neurons. One can anticipate that the valves of decapod hearts are also under nervous control and that this will be important in determining control of the distribution of hemolymph to different portions of the body as demand dictates.

Comparison of crustaceans to molluscs

A review of the other papers from this symposium reveals that several parallels exist between decapod crustacean and molluscan cardiovascular systems. P. J. S. Smith showed that molluscan hearts conform to Starling's Law, but in contrast to crustaceans stretch arises from increased venous return rather than from suspensory ligament recoil. In both phyla SV is a more important variable than f_H in determining CO. In both phyla hormones are powerful modulators of heart function, but a different spectrum of hormones are utilized. M. Kobayashi and K. Kuwasawa showed that the rate and force of beating of the myogenic molluscan heart is under excitatory and inhibitory regulatory nerve control. Acetylcholine may be the inhibitory transmitter. 5HT appears to be the excitatory transmitter in some species (Kuwasawa), but not in others (Kobayashi). The pharmacology of crustacean regulatory nerves differs in that γ-amino butyric acid appears to be the inhibitory transmitter, and acetylcholine or an indol alkylamine the excitatory transmitter (Florey, 1963, quoted in ref. 54).

U. Koch and J. Koester presented evidence for neurally controlled coordination between the cardiovascular, and the respiratory and feeding systems in *Aplysic californica.* Neuronally regulated circulatory switching also occurs in this animal. The analogies with crustaceans are obvious.

Finally, Smith and I noted that most of our information about cardiovascular systems of both phyla has been derived from in vitro preparations. We emphasized the need to apply this knowledge to the in vivo situation if we are to truly understand how the cardiovascular systems are regulated to meet the circulatory demands of the animal.

Abbreviations. CA, cardio-accelerator nerve; CC, circumesophageal connective; CG, cardiac ganglion; CI, cardio-inhibitor nerve; CO, cardiac output; EJP, excitatory junction potential; EMG, electromyogram; EPSP, excitatory postsynaptic potential; f_H, heart rate; IPSP, inhibitory postsynaptic potential; PO, pericardial organ; SV, stroke volume; 5HT, 5-hydroxytryptamine.

Acknowledgments. I wish to thank Eileen Muench for proofreading this manuscript and Dr R. E. Young for helpful discussions and suggestions. Supported by the N.S.E.R.C. of Canada.

1 Alexandrowicz, J. S., The innervation of the heart of the Crustacea. I. Decapoda. Q. J. microsc. Sci. *75* (1932) 181–249.
2 Alexandrowicz, J. S., and Carlisle, D. B., Some experiments on the function of the pericardial organs in Crustacea. J. mar. biol. Ass. U. K. *32* (1953) 175–192.
3 Anderson, M., and Cooke, I. M., Neural activation of the heart of the lobster *Homarus americanus*. J. exp. Biol. *55* (1971) 449–468.
4 Ashbly, E. A., and Larimer, J. L., Modification of cardiac and respiratory rhythms in crayfish following carbohydrate chemoreception. J. cell. comp. Physiol. *65* (1965) 373–380.
5 Battelle, B. A., and Kravitz, E. A., Targets of octopamine action in the lobster: cyclic nucleotide changes and physiological effects in hemolymph, heart and exoskeletal muscle. J. Pharmac. exp. Ther. *205* (1978) 438–448.
6 Belmarich, F. A., and Terwilliger, R. C., Isolation and identification of cardio-excitor hormone from the pericardial organs of *Cancer borealis*. Zool. *6* (1966) 101–106.
7 Belman, B. W., Some aspects of the circulatory physiology of the spiny lobster *Panulirus interruptus*. Mar. Biol. *29* (1975) 295–305.
8 Benson, J. A., Burst reset and frequency control of the neuronal oscillators in the cardiac ganglion of the crab, *Portunus sanguinolentus*. J. exp. Biol. *87* (1980) 285–313.
9 Benson, J. A., Synaptic and regenerative responses of cardiac muscle fibres in the crab, *Portunus sanguinolentus*. J. comp. Physiol. *143* (1981) 349–356.
10 Blatchford, J. G., Hemodynamics of *Carcinus maenas* (L.). Comp. Biochem. Physiol. *39A* (1971) 193–202.
11 Bullock, T. A., and Horridge, G. A., Structure and Function in the Nervous Systems of Invertebrates, pp. 988–997. W. H. Freeman and Co., San Francisco 1965.
12 Burggren, W., Pinder, A., McMahon, B., Wheathly, M., and Doyle, M., Ventilation, circulation and their interactions in the land crab, *Cardiosoma guanhumi*. J. exp. Biol. *117* (1985) 133–154.
13 Butler, P. J., Taylor, E. W., and McMahon, B. R., Respiratory and circulatory changes in the lobster *(Homarus vulgaris)* during long-term exposure to moderate hypoxia. J. exp. Biol. *73* (1978) 131–146.
14 Conant, F. S., and Clark, H. L., On the accelerator and inhibitory nerves to the crab's heart. J. exp. Med. *1* (1896) 341–347.
15 Conner, J. A., Burst activity and cellular interaction in the pacemaker ganglion of the lobster heart. J. exp. Biol. *50* (1969) 275–295.
16 Cooke, I. M., Electrical activity and release of neurosecretory material in crab pericardial organs. Comp. Biochem. Physiol. *13* (1964) 353–366.
17 Cooke, I. M., The sites of action of pericardial organ extract and 5-hydroxytryptamine in the decapod crustacean heart. Am. Zool. *6* (1966) 107–121.
18 Cooke, I. M., and Goldstone, M. W., Fluorescence localization of monoamines in crab neurosecretory structures. J. exp. Biol. *35* (1970) 651–668.
19 Cooke, I. M., and Hartline, D. K., Neurohormonal alteration of integrative properties of the cardiac ganglion of the lobster *Homarus americanus*. J. exp. Biol. *63* (1975) 33–52.
20 Cooke, I. M., and Tazaki, K., Driver potentials isolated in crustacean cardiac ganglion cells by ligaturing. Soc. Neurosci. Abstr. *5* (1979) 494.
21 Evans, P. D., Kravitz, E. A., and Talamo, B. R., Octopamine release at two points along lobster nerve trunks. J. Physiol. *262* (1976) 71–89.
22 Field, L. H., and Larimer, J. L., The cardioregulatory system of crayfish: neuroanatomy and physiology. J. exp. Biol. *62* (1975) 519–530.
23 Florey, E., Studies on the nervous regulation of the heart beat in decapod Crustacea. J. gen. Physiol. *43* (1960) 1061–1081.
24 Florey, E., and Rathmayer, M., The effects of octopamine and other amines on the heart and on neuromuscular transmission in decapod crustaceans: further evidence for a role as neurohormone. Comp. Biochem. Physiol. *61C* (1978) 229–237.
25 George, C. J., Nair, K. K., and Muthe, P. T., The pericardial membrane and its role in crustacean circulation. J. Anim. Morph. Physiol. *2* (1955) 73–78.
26 Hagiwara, S., and Bullock, T. H., Intracellular potentials in pacemaker and integrative neurons of the lobster cardiac ganglion. J. cell. comp. Physiol. *50* (1957) 35–47.
27 Hartline, D. K., Impulse identification and axon mapping of the nine neurons in the cardiac ganglion of the lobster *Homarus americanus*. J. exp. Biol. *47* (1967) 327–340.
28 Hartline, D. K., Integrative neurophysiology of the lobster cardiac ganglion. Am. Zool. *19* (1979) 53–65.
29 Hume, R. I., and Berlind, A., Heart and scaphognathite rate changes in a euryhaline crab, *Carcinus maenas,* exposed to dilute environmental medium. Biol. Bull. *150* (1976) 241–254.
30 Jorgensen, D., Bourne, G., Burnett, L., deFur, P., and McMahon, B., Circulatory function during hypoxia in the dungeness crab, *Cancer magister*. Am. Zool. *22* (1982) 958.
31 Kihara, A., and Kuwasawa, K., A neuroanatomical and electrophysiological analysis of nervous regulation in the heart of an isopod crustacean, *Bathynomus doederleini*. J. comp. Physiol. *154* (1984) 883–894.
32 Kihara, A., Kuwasawa, K., and Yazawa, T., Neural control of the cardio-arterial valves in an isopod crustacean, *Bathynomus doederleini:* excitatory and inhibitory junctional potentials. J. comp. Physiol. *157* (1985) 529–536.

33 Kuramoto, T., and Ebara, A., Effects of perfusion pressure on the isolated heart of the lobster, *Panulirus japonicus*. J. exp. Biol. *109* (1984) 121–140.
34 Kuramoto, T., and Ebara, A., Neurohormonal modulation of the cardiac outflow through the cardioarterial valve in the lobster. J. exp. Biol. *111* (1984) 123–130.
35 Kuramoto, T., and Ebara, A., Effects of perfusion pressure on the bursting neurones in the intact or segmented cardiac ganglion of the lobster, *Panulirus japonicus*. J. Neurosci. Res. *13* (1985) 569–580.
36 Kuramoto, T., and Kuwasawa, K., Ganglionic activation of the myocardium of the lobster, *Panulirus japonicus*. J. comp. Physiol. *139* (1980) 67–76.
37 Lemos, J.R., and Berlind, A., Cyclic adenosine monophosphate mediation of peptide neurohormone effects on the lobster cardiac ganglion. J. exp. Biol. *90* (1981) 307–326.
38 Mangold. E., Studien zur Physiologie des Krebsherzens, besonders über eine aktive Funktion des 'Pericard' bei *Cancer pagurus*. Z. vergl. Physiol. *2* (1925) 184–208.
39 Mayeri, E., Functional organization of the cardiac ganglion of the lobster, *Homarus americanus*. J. gen. Physiol. *62* (1973) 448–472.
40 Maynard, D.M., Activity in a crustacean ganglion. I. Cardioinhibition and acceleration in *Panulirus argus*. Biol. Bull. *104* (1953) 156–170.
41 Maynard, D.M., Circulation and heart function, in: The Physiology of Crustacea, vol. 1, pp. 161–226. Eds H.P. Wolvekamp and T.H. Waterman. Academic Press, New York 1960.
42 Maynard, D.M., Cardiac inhibition in decapod Crustacea, in: Nervous inhibition, pp. 144–178. Ed. E. Florey. Pergamon Press, New York 1961.
43 Maynard, D.M., and Welsh, J.H., Neurohormones of the pericardial organs of brachyuran Crustacea. J. Physiol. *149* (1959) 215–227.
44 McDonald, D.G., McMahon, B.R., and Wood, C.M., Patterns of heart and scaphognathite activity in the crab *Cancer magister*. J. exp. Zool. *202* (1977) 33–44.
45 McMahon, B.R., Physiological responses to reduced oxygen tension in aquatic animals. Am. Zool. (1988) in press.
46 McMahon, B.R., and Wilkens, J.L., Ventilation, perfusion and oxygen consumption, in: The Biology of Crustacea, vol. 2, pp. 289–372. Eds L.H. Mantel and D. Bliss. Academic Press, New York 1983.
47 McMahon, B.R., McDonald, D.G., and Wood, C.M., Ventilation, oxygen uptake and haemolymph oxygen transport, following enforced exhausting activity in the dungeness crab *Cancer magister*. J. exp. Biol. *80* (1979) 271–285.
48 Miller, M.W., and Sullivan, R.E., Some effects of proctolin on the cardiac ganglion of the Maine lobster, *Homarus americanus* (Milne Edwards). J. Neurobiol. *12* (1981) 629–639.
49 Siwicki, K.K., and Bishop, C.A., Mapping of proctolin-like immunoreactivity in the nervous systems of lobster and crayfish. J. comp. Neurol. *243* (1986) 435–453.
50 Sullivan, R.E., Stimulus-coupled ^{3}H-serotonin release from identified neurosecretory fibers in the spiny lobster, *Panulirus interruptus*. Life Sci. *22* (1978) 1429–1438.
51 Sullivan, R.E., A proctolin-like peptide in crab pericardial organs. J. exp. Zool. *210* (1979) 543–552.
52 Sullivan, R.E., and Miller, M.W., Dual effects of proctolin on the rhythmic burst activity of the cardiac ganglion. J. Neurobiol. *15* (1984) 173–196.
53 Sullivan, R.E., Friend, B.J., and Barker, D.L., Structure and function of spiny lobster ligamental nerve plexuses: evidence for synthesis, storage, and secretion of biogenic amines. J. Neurobiol. *8* (1977) 581–605.
54 Taylor, E.W., Control and coordination of ventilation and circulation in crustaceans: responses to hypoxia and exercise. J. exp. Biol. *100* (1982) 289–319.
55 Taylor, E.W., Butler, P.J., and Sherlock, P.J., The respiratory and cardiovascular changes associated with the emersion response of *Carcinus maenas* (L.) during environmental hypoxia, at three different temperatures. J. comp. Physiol. *86* (1973) 95–115.
56 Taylor, H.H., and Greenaway, P., The role of the gills and branchiostegites in gas exchange in a bimodally breathing crab, *Holthuisana transversa:* evidence for a facultative change in the distribution of the respiratory circulation. J. exp. Biol. *111* (1984) 103–121.
57 Tazaki, K., and Cooke, I.M., Spontaneous electrical activity and interaction of large and small cells in cardiac ganglion of the crab, *Portunus sanguinolentus*. J. Neurobiol. *42* (1979a) 975–999.
58 Tazaki, K., and Cooke, I.M., Isolation and characterization of slow, depolarizing responses of cardiac ganglion neurons in the crab, *Portunus sanguinolentus*. J. Neurobiol. *42* (1979b) 1000–1021.
59 Terzuolo, C.A., and Bullock, T.H., Acceleration and inhibition in crustacean ganglion cells. Archs ital. Biol. *96* (1958) 117–134.
60 Watson, W.H. III, and Hoshi, T., Proctolin induces rhythmic contractions and spikes in *Limulus* heart muscle. Am. J. Physiol. *249* (1985) R490–495.
61 Wiersma, C.A.G., and Novitski, E., The mechanism of the nervous regulation of the crayfish heart. J. exp. Biol. *19* (1942) 225–265.
62 Wilkens, J.L., Respiratory and circulatory coordination in decapod crustaceans, in: Locomotion and Energetics in Arthropods, pp. 227–298. Eds C.F. Herreid II and C.R. Fourtner. Plenum Press, New York 1981.
63 Wilkens, J.L., Mercier, A.J., and Evans, J., Cardiac and ventilatory responses to stress and to neurohormonal modulators by the shore crab, *Carcinus maenas*. Comp. Biochem. Physiol. *82C* (1985) 337–343.
64 Wilkens, J.L., Wilkens, L.A., and McMahon, B.R., Central control of cardiac and scaphognathite pacemakers in the crab, *Cancer magister*. J. comp. Physiol. *90* (1974) 89–104.
65 Yazawa, T., and Kuwasawa, K., The cardio-regulator nerves of the hermit crabs: anatomical and electrophysiological and identification of their distribution inside the heart. J. comp. Physiol. *154A* (1984) 871–881.
66 Yazawa, T., and Kuwasawa, K., The cardio-regulator nerves of hermit crabs: multimodal activation of the heart by the accelerator axons. J. comp. Physiol. *155A* (1984) 313–318.
67 Young, R.E., Correlated activities in the cardioregulator nerves and ventilatory system in the Norwegian lobster, *Nephrops norvegicus* (L.). Comp. Biochem. Physiol. *61A* (1978) 387–394.

0014-4754/87/090990-05$1.50 + 0.20/0

Conclusion: Comparative physiology of cardiovascular control

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The symposium on which this multi-author review is based covered a series of related topics centered on neural and neurohumoral control of cardiac output, neural control of the myocardium and circulatory system, and central neural visceral regulation.

Cardiac output

P.J.S. Smith has addressed a fundamental difference in regulation of cardiac performance during a period of increase in tissue demand for delivery of oxygen ('exercise'). The systemic heart of the octopus, unlike the systemic heart of mammals, responds to exercise with increased stroke volume, but no substantial increase in heart rate. This difference is taken as the basis for an enquiry into the underlying cardiovascular control mechanisms in the Mollusca, based on experimental work with the isolated entire heart of *Busycon canaliculatum*. In this preparation both stroke volume and heart rate respond to changes in input perfusion pressure, but significant changes in stroke volume require changes in venous return pressure which seem unlikely in the open cardiovascular system of prosobranch gastropods. This observation led to a consideration of the role of extrinsic factors in