Humans, like most vertebrates, die within minutes when deprived of molecular oxygen (anoxia), in part because of cardiac failure. In contrast, freshwater turtles (genera *Chrysemys* and *Trachemys*) have the ability to survive anoxia for months at low temperatures, but to do so, they drastically suppress cardiac activity and autonomic cardiovascular control (1, 2). Although the cricuar carp (*Carassius carassius*) shares this anoxia tolerance, we show here that this fish can retain normal cardiac performance and autonomic cardiovascular regulation for at least 5 days of anoxia at 8°C. In contrast, its cousin the common carp (*Cyprinus carpio*) survives only 24 hours of severe hypoxia, even though cardiac activity is strongly depressed (3).

Prolonged anoxic survival requires balancing energy supply and demand, as well as coping with the acidosis associated with anaerobic end-product accumulation. Therefore, anoxic freshwater turtles reduce metabolism by 90%, precluding an up-regulation of glycolysis (4), and they buffer lactic acid accumulation with their bone and shell (5). Correspondingly, cardiac output (*Q*) is reduced by 92% (1), and autonomic cardiovascular control is blunted (2). Conversely, anoxic crucian carp remain active, up-regulate glycolysis to maintain their adenosine triphosphate supply, and avoid acidosis by converting lactate into ethanol (6). Thus, we hypothesized that their cardiovascular status and control might be maintained during anoxia. We examined this hypothesis by measuring *Q*, heart rate (*fH*), stroke volume (*V*<sub>s</sub>), ventral aortic blood pressure (*P*<sub>VA</sub>), and respiration rate (*fR*) and by calculating peripheral vascular resistance (*R*) and cardiac power output (*PO*) of crucian carp during 5 days of anoxia at 8 ± 1°C (7).

After an initial adjustment period, *Q*, *fH*, *V*<sub>s</sub>, *PO*, and *R* all returned to pre-anoxic levels throughout days 2 to 5 of anoxia, whereas *P*<sub>VA</sub> and *R* decreased significantly (*P < 0.05*) by 30% and 40%, respectively, indicating vasodilation (Fig. 1). Furthermore, autonomic controls remained intact during anoxia. Cardiac inhibitory cholinergic and excitatory β-adrenergic tones were revealed by respective increases and decreases in both *fH* and *Q* after injections of the pharmacological inhibitors of these control processes (7) (fig. S1, A and C). Tonic α-adrenergic vasoconstriction was revealed by decreased *P*<sub>VA</sub> and *R* after pharmacological α-adrenergic blockade (7) (fig. S1, B and D).

These responses point to an unusual tolerance of a vertebrate heart and autonomic nervous system to prolonged anoxia. Other anoxic hearts either fail immediately, show strongly suppressed activity (turtle and common carp) (1, 3), or lack autonomic control (hagfish) (8). The cricuar carp’s maintained *Q*, reduced *R*, and conserved autonomic control may permit the rapid distribution of glucose from its unusually large liver glycogen store (6) to metabolically active tissues and the transport of waste lactate to the muscle, the sole site of ethanol production (6). Sustained *Q* will also allow for ethanol shuttling to the gills for excretion. Using Fick’s Principle, we estimate a 23% to 85% loss of ethanol from venous blood with each passage through the gills (7). Because ethanol is freely diffusible across the gill epithelia, ethanol excretion is likely perfusion-limited. Therefore, by maintaining *Q* during anoxia, the crucian carp may prevent ethanol accumulation and even intoxication in tissues.

Fig. 1. Cardiorespiratory status of anoxic crucian carp. (A) Stroke volume (blue circles), cardiac output (red squares), cardiac power output (gray triangles), and peripheral resistance (green diamonds) after the indicated period of anoxia. (B) Respiration rate (red hexagons), ventral aortic pressure (blue triangles), and heart rate (white circles). Significant differences (*P < 0.05*; repeated measures analysis of variance, Friedman for percentages; Student-Newman-Keuls posttests) between time zero (normoxic) and hours 48, 72, 96, and 120 for peripheral resistance and ventral aortic blood pressure are indicated by the horizontal, stand-alone blue and green lines, respectively. Values are means ± SEM; *n* = 6 to 18 fish.

References and Notes

7. Materials and methods are available as supporting material on Science Online.
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Supporting Online Material

Supporting Online Material www.sciencemag.org/cgi/content/full/306/5693/77/DC1 Materials and Methods Fig. S1

*S* Supporting Notes

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