

Cardiovascular Adaptive Responses to Heat Stress: A Narrative Review of Hemodynamic, Molecular, and Thermoregulatory Mechanisms

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ABSTRACT

Background. Extreme heat exposure is an intensifying global health threat, with cardiovascular disease representing the leading cause of heat-related mortality. As ambient temperatures continue to rise under accelerating climate change, understanding the physiological mechanisms that govern cardiac and vascular responses to thermal stress has become a scientific and clinical priority.

Objective. This narrative review critically examines and synthesizes current literature on the acute cardiovascular responses to heat stress and the adaptive changes induced by repeated or prolonged thermal exposure, with particular attention to hemodynamic regulation, autonomic control, fluid-electrolyte homeostasis, and molecular cardioprotective mechanisms.

Methods. A comprehensive search of PubMed, Scopus, and Web of Science was conducted for peer-reviewed studies published between 2010 and 2025 using the terms: heat stress, cardiovascular adaptation, thermoregulation, heat acclimation, cardiac output, plasma volume, HSP70, and cutaneous vasodilation. Studies involving human and animal models, experimental and observational designs, were included.

Key findings. Acute heat stress elicits a 50–80% elevation in cardiac output, mediated by heightened heart rate and redistributed peripheral blood flow toward cutaneous vascular beds. Plasma volume reductions of 5–10% through sweating impair stroke volume and accelerate cardiac fatigue. Repeated heat acclimation (10–14 sessions) induces plasma volume expansion of 10–20%, lowers resting core temperature by 0.3–0.5°C, and improves myocardial efficiency through heat shock protein 70 (HSP70)-mediated cytoprotection and endothelial nitric oxide synthase upregulation. Meta-analytic evidence from over 400 laboratory-based heat exposure studies confirms that heart rate increases approximately 27 beats/min per 0.9°C rise in core temperature.

Conclusion. Cardiovascular adaptation to heat stress proceeds through hierarchically organized autonomic, hemodynamic, and molecular pathways. Research gaps remain regarding adaptive phenotypes in populations from arid continental climates, including Central Asia, where occupational heat exposure is prevalent and climate change projections are severe.

Keywords: heat stress; cardiovascular physiology; thermoregulation; heat acclimation; cardiac output; plasma volume expansion; HSP70; autonomic nervous system; arid climate; occupational heat exposure

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1. INTRODUCTION

The physiological relationship between thermal environment and cardiovascular function has been a subject of scientific inquiry since the foundational observations of Claude Bernard and Walter B. Cannon on homeostasis. Yet the urgency of understanding this relationship has never been greater. Global surface temperatures have increased by approximately 1.1°C above pre-industrial baselines, and current projections indicate a likely range of 1.5–3.0°C of additional warming by 2100, even under moderate greenhouse gas emission scenarios (IPCC, 2023). This trajectory translates directly into more frequent, more intense, and

longer-duration heat waves across virtually all inhabited climate zones.

The cardiovascular system occupies a central position in the body's thermoregulatory architecture. It functions simultaneously as a heat transport mechanism, conveying metabolically generated thermal energy from core organs to the cutaneous vascular bed, and as a hydraulic system maintaining perfusion pressure for the brain, kidneys, and working musculature. When ambient temperatures approach or exceed skin temperature, the physics of heat dissipation shift decisively toward evaporative sweating, demanding high cutaneous blood flows that compete with visceral

and cerebral perfusion. This competing hemodynamic demand constitutes the fundamental cardiovascular challenge of heat stress.

Epidemiological evidence robustly confirms the clinical consequences of this physiological strain. A landmark meta-analysis drawing on data from 27 countries documented a 2–5% increase in cardiovascular cause-specific mortality per 1°C elevation above regional temperature thresholds, with ischemic heart disease and cardiac arrest demonstrating the strongest associations (Alahmad et al., 2023). A more recent systematic review, encompassing studies from low- and middle-income countries including Central Asian nations, documented cardiovascular morbidity increases during heat waves even in populations with long ancestral exposure to warm climates (Varghese et al., 2025). These observations underscore the inadequacy of the assumption that physiological acclimatization alone provides population-level protection.

The physiology of cardiovascular heat adaptation encompasses processes operating across multiple scales of biological organization—from whole-body hemodynamics and autonomic neural regulation, through endocrine and renal mechanisms governing fluid homeostasis, to cellular and molecular responses within cardiomyocytes and vascular endothelium. Advances in echocardiographic methodology, cardiac magnetic resonance imaging, microneurographic recording of sympathetic nerve activity, and molecular biology have collectively produced a substantially richer mechanistic understanding over the past decade. The present narrative review aims to synthesize this understanding in an integrative manner, highlighting key quantitative findings, areas of mechanistic consensus, and persistent gaps in knowledge—with a specific perspective on their relevance to populations in arid and semi-arid continental climates.

2. LITERATURE SEARCH STRATEGY

This narrative review was conducted in accordance with the Scale for the Assessment of Narrative Review Articles (SANRA) framework. Database searches were performed in PubMed/MEDLINE, Scopus, and Web of Science in March 2025. The search strategy employed a combination of Medical Subject Headings (MeSH) terms and free-text keywords: (“heat stress” OR “thermal stress” OR “heat exposure”) AND (“cardiovascular” OR “cardiac” OR “heart rate” OR “cardiac output” OR “stroke volume”) AND (“adaptation” OR “acclimation” OR “thermoregulation” OR “physiology”). Additional terms incorporated included “plasma volume,” “HSP70,” “heat shock proteins,” “cutaneous vasodilation,” “autonomic nervous system,” and “dehydration.”

Eligibility criteria included original research articles, systematic reviews, meta-analyses, and high-quality narrative reviews published in English between January 2010 and March 2025. Studies were included if they examined cardiovascular or thermoregulatory parameters during heat exposure or following heat acclimation protocols in human subjects or validated animal models. Case reports, conference abstracts, and non-peer-reviewed sources were excluded. Reference lists of included articles were hand-searched to identify additional relevant sources. A total of 68 publications formed the primary evidence base for this review.

3. ACUTE CARDIOVASCULAR RESPONSES TO HEAT STRESS

3.1 Hemodynamic Redistribution and Cardiac Output

The immediate cardiovascular response to heat exposure is coordinated by the hypothalamus, which integrates thermal afferent signals from peripheral cutaneous thermoreceptors and central thermosensors to generate efferent autonomic commands. Within minutes of entering a hyperthermic environment, withdrawal of sympathetic adrenergic vasoconstrictor tone in the skin, combined with activation of a specific sympathetic cholinergic active vasodilator system, produces dramatic increases in cutaneous blood flow. In thermoneutral conditions, skin blood flow approximates 250 mL/min; during maximal thermal stress, this rises to 6,000–8,000 mL/min, representing a 24–32-fold increase (Kellogg, 2023). This peripheral vasodilation necessitates a compensatory increase in cardiac output to maintain arterial blood pressure. The increase is achieved primarily through heart rate elevation, as the augmented venous return from warm, dilated peripheral vessels partially supports stroke volume through the Frank-Starling mechanism. A comprehensive meta-analysis of over 400 laboratory-based heat exposure studies, encompassing 6,858 participant-exposures, quantified median elevations of 0.9°C in core temperature and 27 beats/min in heart rate from baseline to end of heat exposure (Nature Communications, 2025). Cardiac output rose proportionally, achieving increases of 50–80% above resting values during passive heat exposures at 40–47°C (Foster et al., 2025).

However, the increase in cardiac output is not limitless, and its composition evolves dynamically over the course of prolonged heat exposure. As sweating-induced fluid losses accumulate, plasma volume declines, reducing ventricular filling pressure and progressively attenuating stroke volume. Studies demonstrate that reductions in plasma volume as small as 300–400 mL—achievable within 60–90 minutes of heat exposure at moderate sweat rates—produce measurable

increases in heart rate and reductions in stroke volume at matched thermal loading (Meade et al., 2023). This cardiovascular drift, whereby heart rate rises and stroke volume falls despite constant thermal stimulation, reflects the integration of hypovolemia with the ongoing thermoregulatory demand.

3.2 Autonomic Neural Mechanisms

The autonomic regulation of cardiovascular function during heat stress involves a complex interplay between sympathetic and parasympathetic pathways that has been systematically investigated using microneurography of the peroneal nerve to record muscle sympathetic nerve activity (MSNA). Heat exposure progressively reduces MSNA, reflecting sympathoinhibition to maintain reduced vascular resistance in non-cutaneous beds and enabling the large increases in cutaneous conductance (Wilson, 2023). Paradoxically, cardiac sympathetic activity increases simultaneously, driving the chronotropic response necessary to sustain cardiac output.

Baroreflex function is preserved but resetting occurs during heat stress; the operating point of the arterial baroreflex shifts rightward along the heart rate-pressure curve, allowing higher heart rates at lower mean arterial pressures than would occur under normothermic conditions. This resetting is partially mediated by prostaglandins and nitric oxide released from heated vascular endothelium, which modulate baroreceptor afferent discharge thresholds. Cardiopulmonary baroreflexes contribute additionally to the hemodynamic regulation, sensing reduced central venous pressure from fluid redistribution and activating renal sympathetic discharge to initiate sodium retention.

3.3 Fluid-Electrolyte Dynamics and Endocrine Responses

Thermoregulatory sweating drives substantial fluid and electrolyte losses that impose secondary cardiovascular strain through their effects on plasma volume, blood viscosity, and osmolality. Sweat rates range from 0.5 L/hour under mild heat stress to 2.5 L/hour in heat-acclimatized individuals performing strenuous exercise, with peak rates of 3.5 L/hour documented in elite athletes in hot environments. The sweat ultrafiltrate is hypotonic relative to plasma, meaning fluid losses cause proportionally greater plasma volume reductions than isotonic losses would, and increase plasma osmolality—a powerful stimulus for arginine vasopressin (AVP) release from the posterior pituitary.

AVP-mediated aquaporin-2 upregulation in renal collecting ducts increases free water reabsorption, while concurrent aldosterone secretion, stimulated by both renin-angiotensin activation and elevated plasma potassium, drives sodium reabsorption in the distal nephron. These combined endocrine responses aim to restore plasma volume and osmolality toward baseline, but operate on a timescale of hours, meaning that cardiovascular

compromise from hypovolemia is not fully corrected during acute heat exposure unless exogenous fluid intake is sufficient.

Atrial natriuretic peptide (ANP) secretion, triggered by atrial distension from increased cardiac output, provides a counterregulatory signal that limits excessive fluid retention. The net outcome of these competing endocrine influences determines the extent of plasma volume recovery during and after heat exposure and has important implications for the cardiovascular response trajectory during prolonged or repeated thermal stress.

4. CARDIOVASCULAR ADAPTATIONS TO REPEATED HEAT EXPOSURE (HEAT ACCLIMATION)

4.1 Plasma Volume Expansion: Mechanisms and Magnitude

Among the most consistent and consequential cardiovascular adaptations induced by heat acclimation is expansion of total circulating plasma volume. This hypervolemic response has been documented across diverse acclimation protocols, including exercise-based and passive (rest) regimens, and typically ranges from 10–20% above pre-acclimation values following 10–14 days of daily heat exposure (Tyler et al., 2024). It represents one of the earliest adaptations, becoming statistically detectable after as few as three to five heat sessions.

The primary mechanism driving plasma volume expansion is an acclimation-induced increase in hepatic albumin synthesis, stimulated by the combination of repeated cortisol elevations, upregulated hepatocyte growth factor signaling, and the osmotic challenge of cumulative sweat losses. The resulting rise in plasma colloid osmotic pressure draws interstitial fluid across capillary membranes into the vascular compartment. Aldosterone-mediated renal sodium retention during early acclimation sessions provides an additional osmotic stimulus for fluid redistribution from the interstitium.

The cardiovascular benefits of plasma volume expansion are twofold (Periard et al., 2016). First, increased ventricular filling pressure supports higher stroke volumes at any given heart rate, improving cardiac output efficiency and reducing the chronotropic burden on the heart. Second, the expanded plasma volume increases the thermal heat capacity of blood, improving convective heat transport from core to periphery and potentially allowing slightly reduced cutaneous blood flow requirements at equivalent thermal loads. Together, these effects explain the characteristic adaptation marker of heat acclimation: maintenance of or improvement in cardiac output with a lower heart rate relative to pre-acclimation conditions.

4.2 Thermoregulatory Resetting and Sudomotor Adaptation

Heat acclimation lowers the core temperature threshold at which thermoregulatory effector responses are activated, an adaptation termed resetting of the thermal set-point. In practical terms, acclimated individuals begin sweating and recruiting cutaneous vasodilation at core temperatures 0.3–0.5°C lower than before acclimation, providing a thermodynamic advantage by engaging cooling mechanisms earlier and reducing the peak thermal load imposed on the cardiovascular system (Sawka et al., 2011).

Concomitantly, eccrine sweat gland output increases substantially, both through hypertrophy of individual glands and through earlier recruitment of sweat glands across body surface regions. The composition of sweat shifts toward lower sodium concentration as aldosterone-mediated sodium reabsorption in sweat gland ducts becomes more efficient, reducing electrolyte losses at any given sweat rate and partially protecting plasma osmolality. These sudomotor adaptations collectively enhance evaporative heat dissipation efficiency, which is particularly important in low-humidity environments where convective cooling potential is high.

Resting core temperature declines by 0.3–0.5°C following a complete acclimation protocol, providing a larger thermal buffer before heat illness thresholds are approached. Resting heart rate falls by approximately 5–10 beats/min, reflecting both the expanded plasma volume and the reduced cardiovascular work required for thermoregulation at ambient temperatures below the acclimation stimulus. These resting adaptations have been proposed as candidate biomarkers for monitoring acclimation progression in occupational and sporting contexts (Tyler et al., 2024).

4.3 Endothelial Adaptation and Vascular Remodeling

Beyond hemodynamic adjustments, heat acclimation induces structural and functional remodeling of the vascular endothelium that enhances both thermoregulatory and general cardiovascular function. Endothelial nitric oxide synthase (eNOS) expression and phosphorylation status increase in cutaneous and skeletal muscle vascular beds, augmenting nitric oxide-dependent vasodilation and flow-mediated dilation capacity. Barry et al. (2024) demonstrated using cardiac PET imaging that repeated passive heat exposures produced measurable improvements in myocardial blood flow reserve in individuals with coronary artery disease, suggesting that acclimation-induced vascular adaptations extend to the coronary circulation.

Parallel reductions in endothelin-1 expression and circulating concentrations shift the balance of vasoactive mediators toward vasodilatory dominance, contributing to reduced total peripheral resistance and lower blood pressure after

acclimation. This endothelial adaptation pathway has been leveraged therapeutically in passive heat therapy research, where protocols using hot water immersion or Finnish sauna bathing have demonstrated improvements in brachial artery flow-mediated dilation, arterial compliance, and cardiac function in patients with heart failure and peripheral artery disease (Morris et al., 2025).

5. MOLECULAR AND CELLULAR MECHANISMS OF CARDIOPROTECTION

5.1 The Heat Shock Response and HSP70

At the cellular level, heat stress triggers a rapid and conserved transcriptional program known as the heat shock response, governed by heat shock transcription factor 1 (HSF1). Upon thermal stress, HSF1 undergoes trimerization, nuclear translocation, and binding to heat shock elements (HSE) in the promoter regions of genes encoding heat shock proteins (HSPs). Among this family, inducible HSP70 (encoded by HSPA1A and HSPA1B genes) is the most abundantly expressed isoform in thermally stressed cardiomyocytes, with mRNA induction detectable within 15–30 minutes of supraphysiological temperature exposure and protein accumulation reaching peak levels within 4–8 hours (Kregel, 2002).

HSP70's primary function as a molecular chaperone involves binding nascent, partially folded, or stress-denatured proteins, preventing their aberrant aggregation and either facilitating their refolding to functional conformations in cooperation with co-chaperones (HSP40, HSP90, GRP170) or directing them to proteasomal degradation via the ubiquitin system. In cardiomyocytes specifically, this chaperone function protects the contractile apparatus—myosin heavy chain, troponin T, and sarcomeric actin—from irreversible thermal denaturation that would otherwise compromise cardiac mechanical performance during sustained hyperthermia (Su & Zheng, 2025).

Beyond protein quality control, HSP70 exerts potent anti-apoptotic effects within cardiomyocytes by interrupting multiple steps of the intrinsic mitochondrial apoptosis cascade. It physically interacts with apoptosis-inducing factor (AIF), blocking its nuclear translocation and preventing AIF-mediated chromatin condensation and cell death. It also inhibits cytochrome c-mediated activation of caspase-9 by competing with Apaf-1 for cytochrome c binding. These molecular braking mechanisms confer significant protection against apoptotic cardiomyocyte loss during ischemia-reperfusion injury, heat stroke, and inflammatory cardiac stress, explaining in part why prior heat acclimation reduces myocardial damage in experimental ischemia models.

5.2 NF-κB Pathway Modulation and Anti-inflammatory Effects

Heat stress activates the nuclear factor κ B (NF- κ B) signaling pathway through multiple upstream mechanisms, including reactive oxygen species (ROS) generation, toll-like receptor 4 (TLR4) activation by circulating damage-associated molecular patterns (DAMPs), and direct thermal activation of I κ B kinase (IKK). NF- κ B nuclear translocation drives transcription of pro-inflammatory cytokines (TNF- α , IL-1 β , IL-6), adhesion molecules (ICAM-1, VCAM-1), and complement components that collectively mediate the systemic inflammatory response observed in severe heat stroke (Leon & Bouchama, 2015).

HSP70 accumulation provides counter-regulatory modulation of this inflammatory cascade through direct physical interaction with the IKK complex, reducing its kinase activity and thereby limiting I κ B phosphorylation, degradation, and NF- κ B nuclear translocation. This molecular brake on NF- κ B is considered a primary mechanism underlying acquired thermotolerance—the phenomenon whereby prior sub-lethal heat exposure confers protection against subsequently more severe thermal challenges. The HSP70-NF- κ B axis therefore represents a key molecular intersection between the cellular heat shock response and systemic vascular inflammation.

5.3 TRPV1 Thermosensory Channels and Cardiac Preconditioning

Transient receptor potential vanilloid 1 (TRPV1) channels, widely expressed on cardiac sensory neurons, endothelial cells, and vascular smooth muscle, function as molecular thermometers that initiate signaling cascades in response to temperatures above 43°C or to chemical ligands such as capsaicin and anandamide. TRPV1-mediated calcium influx activates calcineurin-NFAT signaling, eNOS phosphorylation, and substance P release from cardiac afferents, all of which contribute to coronary vasodilation and cardiac preconditioning phenotypes (Caterina et al., 1997).

The preconditioning mechanism involves TRPV1-initiated activation of protein kinase C epsilon (PKC ϵ) and mitochondrial ATP-sensitive potassium channels (mitoKATP), which are the same effector pathways activated by classical ischemic preconditioning. Genetic studies have identified functional polymorphisms in the TRPV1 gene that alter channel thermal sensitivity and are associated with differential thermoregulatory strain and heat tolerance phenotypes in human populations (Bosson et al., 2020). This finding suggests that inter-individual variation in heat-induced cardiovascular responses may have a measurable genetic component operating through the TRPV1 thermosensory pathway.

5.4 Mitochondrial Adaptations

Cardiac mitochondria, which supply 95% of myocardial ATP through oxidative phosphorylation,

are particularly vulnerable to heat-induced functional impairment. Electron transport chain complexes I and III exhibit thermal lability at temperatures above 40°C, with partial uncoupling of proton translocation from ATP synthesis reducing energetic efficiency and increasing ROS generation. Heat acclimation induces mitochondrial biogenesis through upregulation of PGC-1 α (peroxisome proliferator-activated receptor-gamma coactivator-1 alpha), increasing mitochondrial volume density and total oxidative capacity within cardiomyocytes. Concomitantly, mitochondria-targeted antioxidant defenses are enhanced. Manganese superoxide dismutase (MnSOD) expression increases, catalyzing dismutation of superoxide anion to hydrogen peroxide within the mitochondrial matrix and protecting Complex I and Complex III iron-sulfur centers from oxidative inactivation. The thioredoxin-2/peroxiredoxin-3 system also upregulates, providing a complementary peroxide scavenging capacity. These mitochondrial adaptations reduce cardiac energetic inefficiency during thermal stress and limit the mitochondria-driven apoptotic signaling that contributes to cardiomyocyte loss in severe heat stroke.

6. SUMMARY OF KEY CARDIOVASCULAR ADAPTATIONS TO HEAT ACCLIMATION

Parameter	Change After Acclimation	Proposed Mechanism
Plasma volume	+10–20%	Albumin synthesis \uparrow ; aldosterone-mediated Na ⁺ retention
Resting heart rate	–5–10 bpm	Improved preload from plasma expansion; lowered thermal set-point
Resting core temperature	–0.3–0.5°C	Hypothalamic thermoregulatory set-point reset
Sweat onset threshold	–0.3–0.5°C (core temp)	Earlier sudomotor recruitment; enhanced cholinergic sensitivity
Sweat rate	+10–20%	Eccrine gland hypertrophy; increased cholinergic drive

eNOS expression	Upregulated	Shear stress; heat-induced transcriptional activation
HSP70 expression	Upregulated	HSF1 activation; protein quality control demand
Cardiac output efficiency	Improved	Higher SV/HR ratio; reduced rate-pressure product

Table 1. Principal cardiovascular adaptations induced by heat acclimation protocols (10–14 sessions). SV = stroke volume; HR = heart rate; eNOS = endothelial nitric oxide synthase; HSP70 = heat shock protein 70; HSF1 = heat shock transcription factor 1.

7. VULNERABLE POPULATIONS

7.1 Elderly Individuals

Advancing age impairs the cardiovascular response to heat stress through multiple converging mechanisms that collectively reduce thermal tolerance and amplify clinical risk. Age-associated declines in maximum heart rate (approximately 1 beat/min/year after age 20), reduced cardiac compliance, and attenuated diastolic filling limit the degree to which cardiac output can increase in response to peripheral vasodilatory demand. Cutaneous vasodilatory capacity is similarly diminished with aging, owing to reduced endothelial nitric oxide bioavailability, attenuated active vasodilator neurotransmitter release, and structural changes in dermal microvascular architecture (Holowatz et al., 2006).

Foster et al. (2025) exposed healthy young and older adults to standardized dry (47°C, 15% humidity) and humid (41°C, 40% humidity) heat conditions for three hours and assessed cardiac function by echocardiography. While healthy aging did not uniformly abolish the cardiac output augmentation response, older adults showed markedly higher core temperatures at equivalent thermal exposures, higher thermal strain indices, and greater hemodynamic instability during embedded orthostatic challenges. These data suggest that the apparent preservation of cardiac function in healthy elderly individuals conceals a substantially reduced physiological reserve that may be overwhelmed under real-world heat wave conditions involving sleep deprivation, medications, and concurrent illness.

7.2 Outdoor Workers and Occupationally Exposed Populations

Outdoor agricultural, construction, and industrial workers in hot climates face a compounded heat stress burden from simultaneous metabolic heat production and environmental heat gain. The

additive interaction of exercise-generated heat with environmental thermal load substantially magnifies cardiovascular strain relative to either component alone, as the competing demands of locomotor muscle perfusion and cutaneous heat dissipation both require elevated cardiac output. Quantitatively, cardiovascular strain during outdoor labor in 35–40°C heat can approach levels that would be classified as clinically hazardous during heat wave hospital admissions.

A systematic review of heat-related cardiovascular outcomes in low- and middle-income countries, including one study conducted in Kazakhstan and evidence synthesized from comparable arid climate settings, demonstrated consistent associations between occupational heat exposure and cardiovascular morbidity, with risks amplified in agricultural workers lacking cooling infrastructure (Varghese et al., 2025). Progressive dehydration during outdoor work, particularly when cultural, logistical, or organizational factors limit hydration opportunities, accelerates plasma volume depletion and compounds cardiovascular risk. Studies document that workers performing light-to-moderate outdoor labor in hot-dry conditions lose 0.5–1.0 L/hour and may not fully replace these losses voluntarily.

8. RESEARCH GAPS AND FUTURE PERSPECTIVES

Despite the substantial mechanistic knowledge reviewed above, several important questions remain incompletely resolved and represent high-priority targets for future investigation.

First, the question of whether populations with multigenerational residence in arid or semi-arid continental climates—such as Central Asian populations in Uzbekistan, Kazakhstan, and Turkmenistan—exhibit distinct cardiovascular physiological phenotypes compared with populations studied in European or North American contexts remains entirely uncharacterized in the peer-reviewed literature. Physiological phenotyping studies incorporating standardized heat stress protocols, comprehensive hemodynamic measurements, and molecular biomarker profiling (plasma HSP70, cortisol, aldosterone, ANP, and inflammatory cytokines) in these populations would address a significant scientific and public health gap. Second, the interaction between heat acclimation, dehydration, and cardiovascular adaptation—particularly the competing effects of hypovolemia in attenuating versus potentiating certain adaptations—requires clarification. Emerging evidence suggests that mild, transient dehydration during heat acclimation sessions may enhance hormonal and plasma volume adaptations by amplifying aldosterone and AVP responses, while severe hypohydration suppresses the acclimatory phenotype (Periard et al., 2016). Dose-response

characterization of optimal fluid replacement during acclimation protocols has direct practical implications for occupational heat management programs.

Third, sex-specific differences in cardiovascular heat adaptation remain inadequately characterized. A 2025 systematic review and meta-analysis identified that females demonstrate modestly attenuated cardiovascular risk during heat exposure compared with males in some, but not all, epidemiological datasets, with biological mechanisms potentially involving estrogen-mediated endothelial protection and differences in body surface area-to-mass ratio (Zhou et al., 2025). Prospective physiological studies directly comparing the acclimation trajectory and molecular adaptation profiles between sexes are needed.

Fourth, the therapeutic potential of intentional heat acclimation or passive heat therapy for primary and secondary cardiovascular prevention in high-risk populations warrants rigorous investigation. Preliminary evidence from passive heat therapy trials suggests cardioprotective effects in patients with heart failure and coronary artery disease (Morris et al., 2025; Barry et al., 2024), but optimal protocols, dose-response relationships, durability of adaptation, and safety parameters in elderly and medically complex patients remain poorly defined.

9. CONCLUSION

Heat stress challenges the cardiovascular system through demands that span the autonomic, hemodynamic, endocrine, and molecular levels of physiological organization. Acutely, the system responds with cardiac output augmentation driven by heart rate increases and peripheral vasodilation, a response that becomes progressively limited by sweating-induced hypovolemia and the cardiovascular drift that accompanies sustained thermal exposure. The clinical consequence of inadequate compensation—ranging from exertional heat exhaustion to multiorgan heat stroke—represents a cause of preventable cardiovascular mortality whose burden will grow in proportion to global temperature increases.

Repeated heat exposure induces a durable adaptive phenotype centered on plasma volume expansion, thermoregulatory set-point resetting, enhanced sudomotor efficiency, and endothelial remodeling, collectively reducing cardiovascular strain at equivalent thermal loads. At the molecular level, HSP70-mediated cytoprotection and anti-inflammatory NF- κ B modulation provide cardiomyocytes with resistance against heat-induced apoptotic and inflammatory damage, explaining in mechanistic terms why acclimated individuals tolerate heat stress with less cardiac injury than unacclimated counterparts.

The translation of this mechanistic understanding into clinically actionable and policy-relevant

knowledge remains an ongoing challenge. The particularly limited evidence base regarding cardiovascular heat physiology in Central Asian and other arid continental climate populations represents a resolvable gap that would yield both scientific insight into human physiological diversity and practical guidance for occupational and public health authorities facing escalating heat wave risk. Future research should prioritize population-level physiological phenotyping, sex-disaggregated analyses, and the development of evidence-based heat acclimation protocols for occupational deployment in these settings.

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