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STATE-OF-THE-ART REVIEW

Mechanisms of sodium-mediated injury in cardiovascular disease: old play, new scripts

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There is a strong association between salt intake and cardiovascular diseases, particularly hypertension, on the population level. The mechanisms that explain this association remain incompletely understood and appear to extend beyond blood pressure. In this review, we describe some of the 'novel' roles of Na^+ in cardiovascular health and disease: energetic implications of sodium handling in the kidneys; local accumulation in tissue; fluid dynamics; and the role of the microvasculature, with particular focus on the lymphatic system. We describe the interplay between these factors that involves body composition, metabolic signatures, inflammation and composition of the extracellular and intracellular milieus.

Salt-mediated cardiovascular damage: an individualized look beyond blood pressure

A large and diverse body of evidence indicates a close association between salt and high blood pressure (BP), or hypertension, universally recognized as the biggest contributor to the global burden of cardiovascular disease (CVD) and disability [1–4]. Both observational/epidemiological studies [5,6] and randomized controlled interventional trials [7–9] led to the general agreement that a reduction in salt intake in a population translates into lower population-level BP and thereby into reduced mortality and disability-adjusted life-years [10]. The recommended extent of reduction remains, however, debated: some authors endorse a 'the lower, the better' approach [8], while others favour moderate over low intakes, based on a reported J-shaped association with outcomes [11]. At least part of this uncertainty reflects the marked heterogeneity, and to a large extent unpredictability, of the BP response of single individuals to salt loading/unloading: a trait identified as 'salt sensitivity of BP' [12].

As per Guyton's tenets, the concept of salt sensitivity of BP traditionally refers to the impairment in the primarily renal systems devoted to the excretion of salt, or more appropriately sodium (Na^+) [13,14], requiring pressure natriuresis to preserve an even Na^+ balance [15–18]. Others rather point to a subnormal vasodilatory response to salt loading in the absence of any abnormally large increase in renal Na^+ retention

Abbreviations
BP, blood pressure; CVD, cardiovascular disease; EC, extracellular; EH, essential hypertension; GAGs, glycosaminoglycans; IC, intracellular; K^+, potassium; MRI, magnetic resonance imaging; Na^+, sodium; NO, nitric oxide; P, hydraulic pressure; PA, primary aldosteronism; TonEBP, tonicity-responsive enhancer binding protein; VEGF-C, vascular endothelial growth factor C; VEGFR3, vascular endothelial growth factor receptor 3; Π, oncotic pressure.

[19–21]. As a result of these physiological, and genetic, environmental and clinical factors [14,22], the trait is normally distributed in humans and unravelled only by cumbersome and impractical loading tests with arbitrary diagnostic BP cut-offs [23].

Blood pressure is just one single and imperfect, although universally accessible and adopted, biomarker [24] to assess salt-related cardiovascular risk and disease, even among hypertensive patients. There is now direct preclinical and ultimately clinical [25] evidence, suggesting that excess Na^+ can adversely affect cardiovascular health independent of BP. Others have already reviewed the topic [26–28] by discussing effects of Na^+ on not only vascular function [29–33], stroke risk and cerebrovascular autoregulation [34–36], but also bone health and osteoporosis [37] or immune mechanisms [38].

Here, we will not systematically cover cardiocerebrorenovascular Na^+-mediated damage: we will rather highlight mechanisms of Na^+ handling and Na^+-related injury, which emerged in the last few years, may vary widely across individuals and are not necessarily reflected by BP changes. While they could also impact on CVDs other than hypertension, their understanding is still preliminary and actively evolving.

Sodium and energetics

Recent work suggested a BP-independent link between high Na^+ intake and a global shift in metabolism, driven by the ultimate need to preserve water upon this dietary habit. The original observation was made in a human long-term Na^+ balance study during Russian spaceflight simulations [39]. The investigators modified the salt intake of ten healthy, young and male cosmonauts over 3.5–7 months and collected daily 24-h urine samples. Although the study was not devoid of limitations [40], the unique human experimental setting offered unprecedented control of diet and environment over a remarkably long period of time. At variance with previous human investigations, largely based on unphysiological short-term shifts from very low to high salt intakes, the authors reported large infradian changes in total body Na^+ without parallel changes in body weight [39] and a decrease in water intake with high-salt diet, opposite to the expected increase [41]. Despite this, urine volumes remained unchanged. To reconcile the mismatch, the authors advocated surplus endogenous free water generation from exaggerated catabolic reactions and from enhanced renal accrual, which would make any extra exogenous water intake unnecessary. The hypothesis was tested in rodent models, where urea excess was found to be a key osmotic force to minimize free water loss, via renal recycling and extrarenal generation [42]. The latter resulted from a salt-driven catabolic state, with muscle mass loss and protein breakdown as a source for urea, as well as from reprioritisation of global energy metabolism.

We have recently confirmed that water-preserving mechanisms are activated upon high Na^+ intake in a large real-life cohort of patients with essential hypertension (EH). Patients exhibited glomerular hyperfiltration and excess Na^+ load to the tubuli, resulting in increased tubular energy expenditure for its reabsorption [43] (Fig. 1, top). Preliminary data from patients with primary aldosteronism (PA), a prototypic form of salt-sensitive hypertension featuring glomerular hyperfiltration and excessive tubular Na^+ reabsorption regardless of intake [44,45], point to similar conclusions (Fig. 1, bottom). In EH, these renal-specific changes were associated with peripheral metabolomics signatures suggestive of protein catabolism, from either endogenous or exogenous sources [43]. We therefore suggested that the kidneys are the primary determinants of the underlying energy imbalance, a proposal that is in keeping with the dependence of cardiovascular energy expenditure on renal sympathetic nerve activity in rats fed the high salt [46]. We cannot exclude, however, that additional mechanisms such as systemic hypercortisolism [42] also play a role.

Other authors conducted secondary analyses of the randomized DASH–sodium trial [7] and concluded, by reversing the investigational perspective, that low salt intake did not require reduced energy intake to keep weight stable [47]. In the study, however, weight did vary across study arms, and in the absence of calorimetry measures for body composition, unambiguous conclusions cannot be drawn. A conclusive randomized clinical trial to 'end the salt wars' [48] is still awaited.

Despite the need for further mechanistic confirmations, we consider the effect of high salt intake on metabolic pathways an important factor impacting cardiovascular health. In particular, metabolic effects of salt could significantly contribute to the prevalent clustering of diabetes, dyslipidaemia and obesity, with or without hypertension, in high-salt-consuming populations [49], even independent of energy intake [50]. Excess exploitation of endogenous proteins leading to lean mass loss (sarcopenia) or of exogenous (food) sources would ultimately result in insulin resistance [51] or excess fat deposition, regardless of food relative content [52] (Fig. 1). Such body changes, along with additional mechanisms described herein below, directly impact tissue microcomposition.

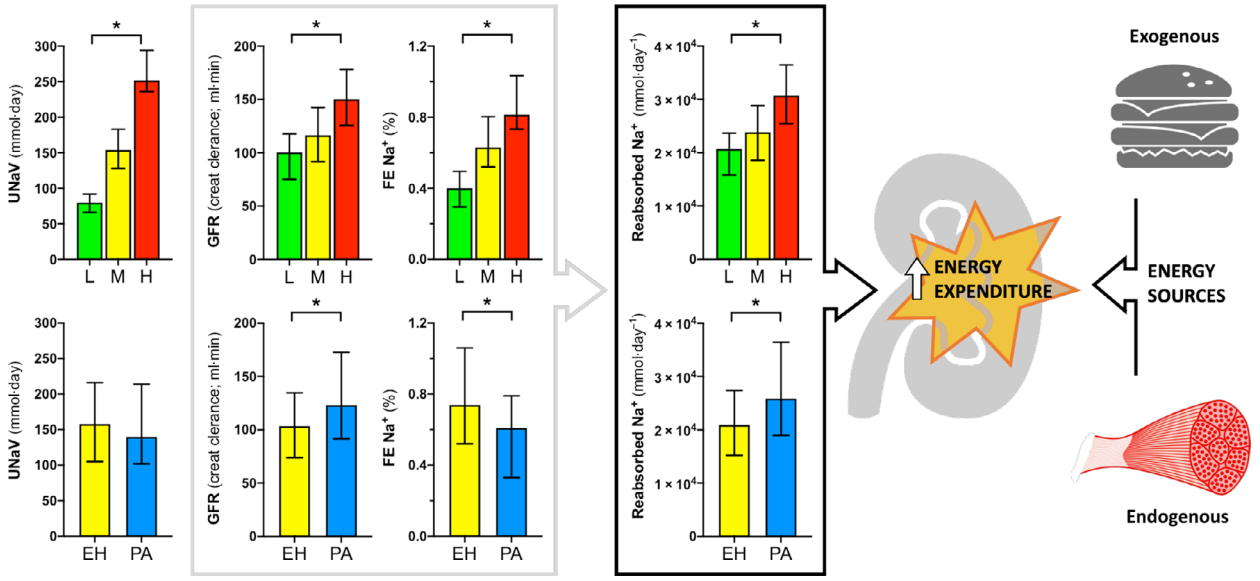

Fig. 1. Excess Na^+ load to the tubuli, as a result of (top) high Na^+ intake and secondary glomerular hyperfiltration in patients with EH (panels modified from Rossitto *et al.* [43]), or (bottom) of PA, featuring glomerular hyperfiltration (middle) and enhanced distal Na^+ reabsorption leading to lower fraction (FE) in comparison with EH (right) despite similar intake (left), translates into a higher absolute amount of reabsorbed Na^+ (black-contoured panels) and requires excess energy consumption. This energy can be generated by catabolism of exogenous (via excess food intake) or endogenous (leading to relative sarcopenia) sources. uNaV, urinary Na^+ excretion, as an estimate of Na^+ intake; GFR, glomerular filtration rate; FE, fractional excretion; L: low Na^+ intake (< 2.3 g Na^+·day^{-1}); M: medium Na^+ intake (2.3–5 g Na^+·day^{-1}); and H: high Na^+ intake (> 5 g Na^+·day^{-1}). Bottom panels depict unpublished data from the same original study cohort of Rossitto *et al.* [43], collected in PA with the same methodology already reported for EH patients. All data are shown as median and interquartile range; intergroup comparisons by Tukey's or Dunn's *post hoc* tests for top panels [43] and Student's *t*-test or Mann–Whitney *U* test for bottom panels, as appropriate; $*P < 0.05$.

Sodium balance and interstitium

Implications of long-term (im)balance studies and the nature of tissue sodium accumulation

Physiology classically advocates the ultimate achievement of a balance between salt intake and excretion [53], with Na^+ closely paralleled by commensurate water to maintain body fluid tonicity homeostasis [54]. At variance, the aforementioned 'spaceflight' and other previous studies [55] identified large changes in total body Na^+ without parallel changes in body weight [39], a surrogate of water. This was interpreted in the context of 'osmotically inactive' Na^+ accumulation. Similar salt-loading studies, conducted in rodent models of normotension, salt-resistant and salt-sensitive hypertension, revealed differences in total body Na^+ and Na^+-associated volumes across groups and an apparent dissociation of Na^+ and water tissue contents [56]. The analytical separation of body compartments suggested the existence of a skin-specific hypertonic Na^+ depot [57,58], identified in the extracellular matrix and particularly in the negatively charged glycosaminoglycans (GAGs) network, which increased in content and sulfation upon salt loading [59]. A local self-regulatory system triggered by the osmo sensor tonicity-responsive enhancer binding protein (TonEBP) would facilitate interstitial Na^+ clearance (see next section) [60–62], as its disruption led to excess skin Na^+ accumulation in the animals and, remarkably, salt-sensitive hypertension.

In humans, similar evidence of skin Na^+ excess has been found in many CVDs or associated risk factors, such as older age and hypertension [63,64]; diabetes [65]; chronic kidney disease [66]; acute heart failure [67]; and sclerodermic [68] or infected skin [69], by means of ^{23}Na magnetic resonance imaging (MRI). However, in most of these MRI studies also skeletal muscle, and more recently myocardium in patients with PA [70], showed high Na^+ signal. This questions the originally proposed skin specificity of the phenomenon; moreover, the dual osmotically active and inactive nature of interstitial Na^+, driving TonEBP-mediated signalling while simultaneously eluding parallel and commensurate water accrual, appeared somehow equivocal. In fact, our recent whole-body composition study identified excess tissue Na^+ not only in skin but also in other organs of Na^+-loaded rats,

without evidence of hypertonic Na^+ accumulation [71]. The results demonstrated that changes in whole-tissue Na^+ concentration do not necessarily reflect hypertonicity: in keeping with a 'histochemical deductive approach' of the 1940s biochemists [72–74], Na^+ and K^+ concentrations in the whole tissue are *per se* function of the tissue extracellular (EC)-to-intracellular (IC) volume ratio [75], being Na^+ the most abundant cation in the EC and K^+ in the IC space, respectively. Unless their sum ($Na^+ + K^+$) is increased above physiological levels, the one is increased and the other reduced by simple changes in EC relative volume. In many studies investigating the topic, and certainly those relying on the signal from a single isotope, like ^{23}Na-MRI studies, assessment of this sum is lacking.

Human skin, particularly in the context of hypertensive ageing, makes no exception [71], despite the suggested parallels between specific subepidermal anatomy and physiology with renal medulla [76]. Given the lack of conclusive evidence for this analogy and the enormous energetic cost that generation and maintenance of local hypertonicity via active Na^+ transport would require, we believe that the findings of water-paralleled accumulation are simply more plausible. This conclusion is supported by independent reports [77], including those of isotonic skin interstitial fluid even upon salt loading [78]. It is appreciated, however, that precise measurement of tissue water and electrolyte content is extremely challenging and different conclusions can be the result of different methodological approaches.

The 'site' of accumulation

The originally proposed site for Na^+ accumulation was the interstitial GAG network [59]. This prompts a couple of considerations. First, both chemical 'destructive' and ^{23}Na-MRI approaches give a 'whole-tissue' readout, which cannot discriminate EC from IC space [75]. Whether excess EC Na^+ is mechanistically linked to an increase also in IC Na^+ depends on the activity of multiple channels and pumps and largely remains an unexplored question. Based on established [79] and novel evidence [80–82] of high intracellular Na^+ impacting on cellular metabolism, this closely links to the global metabolic changes discussed in the previous section. Second, the argument of a high-salt diet-induced modulation of skin GAGs [59] or their correlation with tissue Na^+ content [83] lends *per se* no support to a water-free binding of Na^+ to their negative moieties: GAGs have prominent hygroscopic properties, and they normally bind water molecules, in addition to Na^+, to guarantee cartilage function in joints. As for Na^+ [83], a strong association was reported for skin GAGs and water content in patients with heart failure [84]. In fact, to the best of our knowledge, no measured Na^+-to-water stoichiometry of binding to tissue GAGs is available for any human CVD. What is clearly established, on the contrary, is that GAGs are key components of the EC matrix [85] and accumulation of interstitial Na^+ in the isotonic form of oedema, by exerting biophysical forces, may well affect local mechanosensing, the phenotype of surrounding cells and, ultimately, the remodelling of matrix itself [86,87]. Arthur Guyton foresaw such EC plasticity when alluded to 'tissue fluids, pressures and gels' [13].

Collectively, studies conducted in the macroscopic scale of whole-tissue analysis cannot unequivocally exclude the occurrence of hypertonic accumulation of Na^+ in microscopic 'niches' (see next section), but the macroscopic and highly prevalent excess revealed in human tissues by ^{23}Na-MRI signal should be generally regarded as a measure of EC volume expansion and oedema. Its clinical relevance is suggested by the strong association with target organ damage, for example left ventricular hypertrophy in the typically salt-sensitive population of patients with chronic kidney disease [66].

Tissue sodium as a measure of EC volume

The above considerations by no means detract value from the novel concept of tissue Na^+ accumulation [88], which challenged the dogma of even salt balance [53]. In the short-term, experimental evidence of a body weight gain 'commensurate to iso-osmolar water retention' in salt-sensitive compared with salt-resistant subjects [89] already supports our contention. In the long term, future assessment of this balance will probably have to take into consideration the limited sensitivity of water compared with Na^+ in the identification of oedema [75]; the dissociation of their renal handling upon conditions of depletion/excess [41–43]; commonly overlooked nonrenal routes for their elimination [90–92]; and, most importantly, dynamic changes in the EC-to-IC composition of tissues. With regard to the latter, a change in EC-to-IC volume proportions could be an active adaptive mechanism to 'accommodate' Na^+ space and preserve osmolality without necessarily keeping excess water on board, as per Cannon's homeostasis [53]. Involvement of TonEBP, a master regulator of cellular responses to osmotic stress [93,94], is speculative at the moment. On the other hand, it could be the passive result of a Na^+-related catabolic state, reducing 'cellularity' in different tissues and changing many reference parameters involved in or

affecting the balance. In other words, whichever the active or passive reason, Na^+ retention with isotonic expansion of the EC volume does not necessarily require a positive water balance, if the 'cellular mass' is reduced (Fig. 2).

Of note, EC volume expansion is not synonymous with intravascular volume, and in patients with hypertension [95,96], or more overtly in conditions such as heart failure [97,98], it may well preferentially involve the interstitial compartment. While speculations on a direct impact on organ function are tempting, for example in the myocardium [99] or the vascular wall [100,101], the actual biophysical, molecular and ultimately clinical implications of such

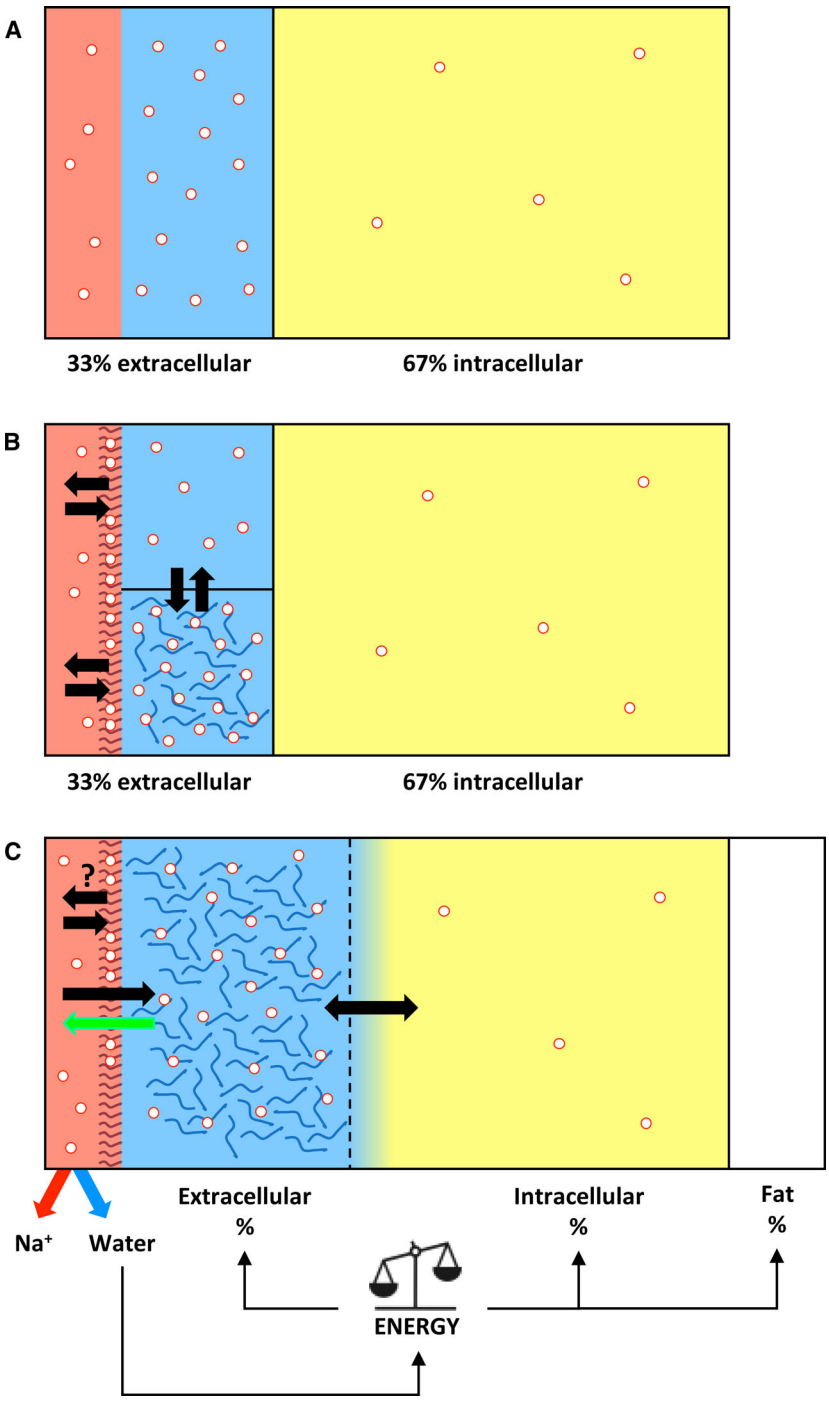

Fig. 2. (A) 'Classic' distribution of fluids and Na^+ (○) in the intracellular and extracellular space, including intravascular (light red) and extravascular (light blue) compartments. (B) Model accounting for hypertonic (water-independent) accumulation of Na^+ in the interstitium and in the endothelial surface layer (glycocalyx; adapted from Olde Engberink *et al.* [145]). (C) Model reconciling an excess tissue Na^+ content and concentration with overall ECV isotonicity; microscopic niches of water-independent accumulation (i.e. in the glycocalyx) cannot be excluded ('?' in the panel). ICV-to-ECV ratio, which translates into tissue Na^+ content, is modulated passively by energy balance and metabolic status (± fat deposition; see the section on energetics) and/or actively by cellular plasticity (double arrow) to accommodate unexcreted excess body Na^+. Such response could involve cellular TonEBP signalling. Excess isotonic Na^+ in the interstitium, as a result of excess extravasation (black rightward arrow), triggers anatomical and functional lymphatic expansion for removal (green leftward arrow; see next session). Dissociation of Na^+ from water excretion (red and blue arrows) via renal and nonrenal routes, although energetically demanding, preserves whole-body water homeostasis.

expansion largely remain unexplored. For sure, EC volume expansion is known to portend ominous prognosis when overt, as in heart failure [98].

Sodium, microvessels and interstitial fluid dynamics

Reappraisal of microvascular dynamics

If tissue Na^+ has to be primarily regarded as a surrogate of EC volume, a relevant focus of research should be on microcirculation, where the exchange of fluids between plasma and the perivascular interstitial space takes place. For more than a century, this phenomenon has been interpreted according to the Starling–Landis principle, whereby the rate of filtration is proportional to the hydraulic pressure gradient between plasma and interstitium ($P_p - P_i$) minus the opposing oncotic gradient ($\Pi_p - \Pi_i$) [102]. Contemporary evidence, based on direct measurements and appreciation of the structural complexity of the microvascular wall, revealed that the net sum of forces favours filtration over absorption along the entire length of the microvessels [103], rather than a sustained reabsorption of interstitial fluid at the venous end of the capillary bed (Fig. 3).

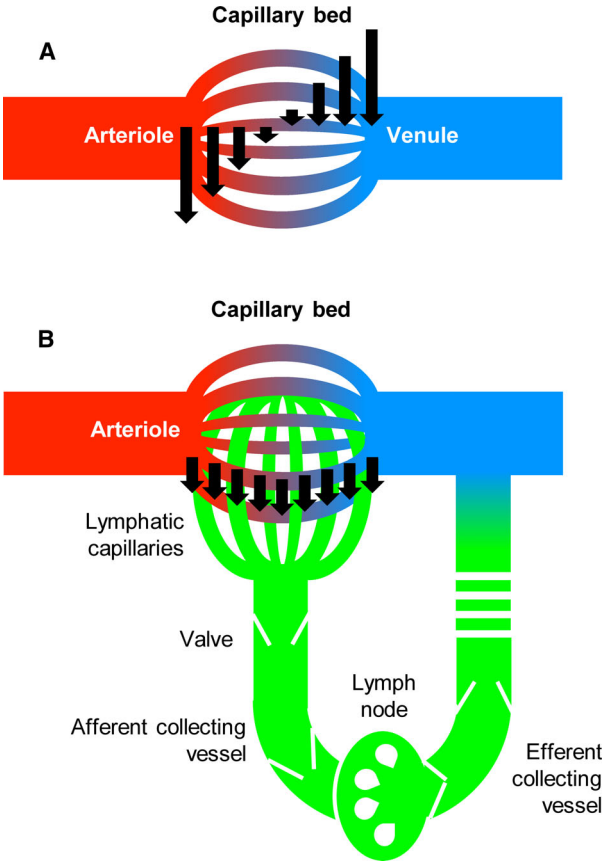

Fig. 3. (A) Traditional arteriovenocentric understanding of Starling equilibrium, assuming negligible interstitial forces and reabsorption of fluids at the venous end of the microvascular bed, accordingly. (B) Reappraisal of the above, accounting for the role of glycocalyx in the control of fluid filtration and for directly measured interstitial forces, which result in a constantly positive sum of outward forces along the entire capillary bed [103]; the filtered fluid is returned to the central venous blood by the lymphatic system.

Glycocalyx and endothelium

The first key layer encountered by fluids and solutes in the process of extravasation at the capillary-to-interstitium interface is the endothelial surface layer, or glycocalyx. It is composed of glycosamino- and proteoglycans, regulated in length and composition by the shear forces of the flowing blood [104–106]. As such, it modulates many endothelial functions, including transition from quiescence to activation towards leucocyte adhesion/extravasation, as well as nitric oxide (NO) production in response to transduced biomechanical signals [107]. In addition, it crucially controls filtration: conditions such as diabetes, end-stage kidney disease or even sepsis, where the thickness and integrity of the glycocalyx is affected [108–110], are associated with excess vascular permeability. In keeping with the speculations regarding interstitial GAGs, some authors suggested that the endothelial glycocalyx could bind excess Na^+ and serve as a first Na^+ buffer [111], protecting from interstitial accumulation. As for the interstitial space, the exact stoichiometry of local Na^+-to-water dynamics within and across this ultrathin layer remains unclear. In this case, even macroscopic evidence of preserved isotonicity in tissues cannot exclude a 'microscopic' hypertonicity exerting specific biological actions on circulating and adhering immune or vascular endothelial cells.

Preservation of glycocalyx thickness limits the extravasation of fluids for biophysical reasons, including the microscopic modulation of oncotic gradients, as extensively reviewed elsewhere [102,103]. On the contrary, exposure to high Na^+ conditions *in vitro* makes the glycocalyx stiffer and thinner, thus facilitating the entry of Na^+ into the endothelium [112]. The biophysical properties (increased stiffness) and function (reduced NO release) of this second layer, encountered by extravasating fluids immediately after the glycocalyx, are similarly affected by such Na^+ excess [113]. Overall, this suggests intravascular mechanisms of protection from excess Na^+ and fluid filtration,

which may be impaired in conditions of Na^+-related disease by a self-sustaining vicious circle.

Lymphatic vessels

Once the endothelial surface and cellular layers have been trespassed, the lack of sustained reabsorption of fluid from the venous capillaries in most clinical/anatomical conditions [102] implicates other routes for drainage, offered by the lymphatic system (Fig. 3). By transporting lymph back to the central veins, lymphatic vessels maintain tissue volume homeostasis. To do so, they not only are ubiquitous [114] but they also show a highly sophisticated anatomy and function. Lymphatic vessels are organized into series of lymphatic capillaries, precollecting vessels and collecting vessels that ultimately drain into the thoracic or right lymphatic duct and the subclavian veins. The specific anchoring with the matrix and the buttonlike junctions in the blind-ended capillaries (opened and closed by interstitial-to-intravascular pressure gradients for the controlled entry of solutes, macromolecules and cells), the contractile activity of the peri-endothelial lymphatic muscle cells in collectors and the one-way valves separating the in-series functional units (each called 'lymphangion') confer unidirectionality [115,116]. Of note, the contractile activity remarkably shares functional aspects with the myocardium, including pacemaker-generated action potentials for coordination of vascular systole and diastole and the sensitivity of the contractile machinery to external stimuli, for example preload [115,117,118]. Therefore, it is no surprise that the accumulation of 'salty' interstitial fluid potentiates its drainage by lymphatics: excess tissue Na^+ upon salt loading has been shown to induce the plastic expansion of the lymphatic vascular network [60,61] and to increase lymph flow [62]. The lymphangiogenic response is dependent on TonEBP activation in resident mononuclear phagocytic cells, with downstream signalling involving VEGF-C secretion and VEGFR3 activation: *in vivo* depletion of mononuclear cells [60], conditional phagocyte-specific deletion of TonEBP [61] and VEGF receptor blockade [61,119] led to hypoplastic capillaries and excess Na^+ accumulation. The exact mechanisms of TonEBP activation, confirmed in rodent models even in the context of a 'macroscopically' isotonic ECV [71], still require clarification; however, they may involve changes in the biophysical properties of the interstitium upon oedema accumulation, as reported for mechanically stretched vascular smooth muscle cells [120].

After the first reports of Na^+-induced expansion [60,61], enhanced cardiac lymphangiogenesis by VEGF-C was shown to reduce myocardial fibrosis and macrophage infiltration, decrease BP and preserve myocardial function in a salt-sensitive rat model of hypertension, while VEGF-C blockade produced opposite effects [121]; similarly, an inducible genetic model of kidney-specific lymphangiogenesis proved resistant to the development of hypertension induced by high-salt diet [122], as well as by multiple other prohypertensive stimuli [123,124]. In the broader context of CVD at large, increased lymphatic flow was also shown to facilitate resolution of postischaemic myocardial oedema and improve cardiac function in rodent models [125]; similar roles for lymphatics are emerging also in obesity, diabetes and atherosclerosis, as reviewed elsewhere [115,116,126–128].

Overall, all such evidence led to the appreciation of lymphatics as key regulators of local Na^+ and fluid homeostasis in a broad range of conditions where tissue oedema occurs [129]. However, this pathophysiological appreciation contrasts with a still scant evidence of a lymphangiogenic or lymphatic defect in human Na^+ excess-associated disease. Recently, our group demonstrated a defective lymphatic reserve in patients with heart failure compared with healthy controls of similar age and sex [130]. This led to an earlier onset of tissue fluid accumulation when venous pressure was increased. Similar investigations, aimed at dissecting the anatomical and functional complexity of lymphatics in conditions where tissue Na^+ and fluid excess is more subtle, will better clarify the role of this frequently neglected arm of the circulation in human CVD. Based on the established role played by inflammation in CVD, these investigations should not ignore the immunomodulatory – in addition to hydraulic – function that these vessels locally exert.

Local sodium excess and inflammatory cells

Once Na^+ accumulates in tissues, either because of exposure to an excessive load or because of defective drainage, it does produce biological effects. We have previously alluded to the possibility of a secondary EC matrix remodelling, which would perpetuate EC volume expansion and would likely impact the function of the more 'noble' IC component of tissues, although related mechanisms and the extent of such impact remain largely unexplored. On the contrary, it is now well established that excess Na^+ intake and accumulation can modulate the function of immune cells [131]. We will just briefly touch on it for what pertains aspects discussed above, and refer the reader to another recent review on the complexity of the topic

[38]; at variance with 'hypertonic tissue environments', we just see therein discussed 'diet-dependent and diet-independent' Na^+ accumulations as reflective of ECV expansion (with or without oedema).

The initial report of skin resident mononuclear phagocytic cell activation upon salt loading [60] was followed by many others, describing the activation of pathogenic immune-inflammatory cells upon culture in supraphysiological concentrations of Na^+. In particular, hypertonic extracellular Na^+ was found to stimulate proinflammatory [69,132,133] and to inhibit anti-inflammatory [134,135] macrophages and T cells, respectively; dendritic cells, presenting antigens and coactivating T cells, are similarly affected [136,137]. In physiological conditions, these mechanisms appear to play an important role in host defence: in the renal medulla, where hypertonic Na^+ gradients are actively maintained, hypersalinity enhances mononuclear phagocytes bactericidal activity and cytokine production to generate a zone of defence; patients with urinary concentrating defects are susceptible to kidney infections [138]. However, it remains unclear whether and how a similar Na^+-induced overactivation of immune cells occurs *in vivo* in tissues or conditions where such hypertonicity seems lacking. Tissue biophysical changes or microscopic niches, as discussed, may well play a role. In this sense, even microgradients impacting appropriate sensors [139] may induce spatial and phenotypic polarization of cells, which may explain the increased leucocyte adhesion to the vascular endothelium under high Na^+ conditions; alternatively, enhanced transvascular migration of immune cells could directly result from the biophysical stiffening or rarefaction/thinning of the glycocalyx [112,140–142].

Importantly, the established dysregulation of immune cells upon conditions of salt excess, including the possible modulation by epigenetic changes [143], may involve mechanisms other than the local environment: these would entail diet-induced modulation of the microbiome, neuro-hormonal axes [38,144] and, we contend, all the long-term compensatory responses to them.

All in all, Na^+-induced overactivation of immune cells has the potential to promote an inflammatory status that is known to underlie organ damage in hypertension and many other cardiovascular conditions; in humans, the exact mechanisms of this activation still lack precise characterization.

Conclusions

In this review, we described some of the 'novel' roles of Na^+ in cardiovascular health and disease, focussing on energetics implications, local accumulation, fluid dynamics and the role of the microvasculature with particular focus on the lymphatic system. The suggested changes in metabolism may directly or indirectly impact on body composition, and therefore not only on aspects such as insulin sensitivity but also on systemic IC-to-EC volume ratio, which links to interstitial Na^+. The interplay between the latter, the microvasculature and inflammatory responses contributes to systemic, as well as local, inflammatory implications of salt excess in organ damage. This complexity of Na^+ homeostasis explains why simple cut-offs for or 'safe' ranges of Na^+ intake cannot be easily applied to different disease scenarios. Accordingly, 'salt sensitivity' appears to be a complex phenotype, regulated by a multitude of factors, and BP response cannot remain the sole clinical readout to assess the susceptibility of an individual to the effects of Na^+ excess if other factors including microvascular changes and inflammatory response are neglected. Most of these aspects remain incompletely elucidated, particularly in relation to human disease. However, they identify Na^+ as a *fil rouge* linking derangements in metabolic, renal, vascular and ultimately interstitial function, even independent of BP values, in the frequently comorbid population of patients with CVD. Appreciation of the prevalence and broad biological relevance of isotonic tissue Na^+ accumulation in tissues should prompt its identification in these patients at earlier stages of disease, long before it results in obvious 'congestion' like in heart failure or end-stage CKD.

To conclude, the play of Na^+ in CVD is clearly a very old one, but the last years of research, with occasional waves of enthusiasms along with others of neglect, have changed the scripts. They now include the following: new acts, on the energetic implications of Na^+ handling, in relation to renal function and to energy sources availability/access; *coupes de théâtre*, with the disproof of a long-term even balance in relation to Na^+ accumulation in tissues, regarded by us as a measure of qualitative and quantitative changes in systemic EC volume; new sceneries, moving the story of Na^+ control down to the depths of capillary interface and interstitium; and new characters, like the dedicated and duty-driven but only apparently tireless sweepers played by lymphatics, or the two-face immune cells, friends or foes at varying times. *Ça va sans dire*, we are excited to see the drama unfolding.

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Conflict of interest

The authors declare no conflict of interest.

Author contributions

CD and GR both substantially contributed to the conception and design of the article and interpreting the relevant literature. GR drafted the article. CD revised it critically for important intellectual content.

References

1 Chow CK, Teo KK, Rangarajan S, Islam S, Gupta R, Avezum A, Bahonar A, Chifamba J, Dagenais G, Diaz R *et al*. (2013) Prevalence, awareness, treatment, and control of hypertension in rural and urban communities in high-, middle-, and low-income countries. *JAMA* **310**, 959–968.

2 Forouzanfar MH, Liu P, Roth GA, Ng M, Biryukov S, Marczak L, Alexander L, Estep K, Hassen Abate K, Akinyemiju TF *et al*. (2017) Global burden of hypertension and systolic blood pressure of at least 110 to 115 mm Hg, 1990–2015. *JAMA* **317**, 165–182.

3 Williams B, Mancia G, Spiering W, Agabiti Rosei E, Azizi M, Burnier M, Clement DL, Coca A, de Simone G, Dominiczak A *et al*. (2018) 2018 ESC/ESH guidelines for the management of arterial hypertension. *Eur Heart J* **39**, 3021–3104.

4 Murray CJ & Lopez AD (2013) Measuring the global burden of disease. *N Engl J Med* **369**, 448–457.

5 Prior IA, Evans JG, Harvey HP, Davidson F & Lindsey M (1968) Sodium intake and blood pressure in two Polynesian populations. *N Engl J Med* **279**, 515–520.

6 Intersalt Cooperative Research Group (1988) Intersalt: an international study of electrolyte excretion and blood pressure. Results for 24 hour urinary sodium and potassium excretion. *BMJ* **297**, 319–328.

7 Sacks FM, Svetkey LP, Vollmer WM, Appel LJ, Bray GA, Harsha D, Obarzanek E, Conlin PR, Miller ER, Simons-Morton DG *et al*. (2001) Effects on blood pressure of reduced dietary sodium and the Dietary Approaches to Stop Hypertension (DASH) diet. DASH-Sodium Collaborative Research Group. *N Engl J Med* **344**, 3–10.

8 He FJ, Tan M, Ma Y & MacGregor GA (2020) Salt reduction to prevent hypertension and cardiovascular disease: JACC state-of-the-art review. *J Am Coll Cardiol* **75**, 632–647.

9 Filippini T, Malavolti M, Whelton PK, Naska A, Orsini N & Vinceti M (2021) Blood pressure effects of sodium reduction: dose-response meta-analysis of experimental studies. *Circulation* **143**, 1542–1567.

10 Collaborators GD (2019) Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. *Lancet* **393**, 1958–1972.

11 O'Donnell M, Mente A, Alderman MH, Brady AJB, Diaz R, Gupta R, López-Jaramillo P, Luft FC, Lüscher TF, Mancia G *et al*. (2020) Salt and cardiovascular disease: insufficient evidence to recommend low sodium intake. *Eur Heart J* **41**, 3363–3373.

12 Weinberger MH, Miller JZ, Luft FC, Grim CE & Fineberg NS (1986) Definitions and characteristics of sodium sensitivity and blood pressure resistance. *Hypertension* **8**, II127–II134.

13 Guyton AC, Coleman TG & Granger HJ (1972) Circulation: overall regulation. *Annu Rev Physiol* **34**, 13–46.

14 Elijovich F, Weinberger MH, Anderson CA, Appel LJ, Bursztyn M, Cook NR, Dart RA, Newton-Cheh CH, Sacks FM & Laffer CL (2016) Salt sensitivity of blood pressure: a scientific statement from the American Heart Association. *Hypertension* **68**, e7–e46.

15 Guyton AC & Hall JE (2011) Textbook of Medical Physiology. Elsevier, Philadelphia, PA.

16 Guyton AC, Coleman TG, Young DB, Lohmeier TE & DeClue JW (1980) Salt balance and long-term blood pressure control. *Annu Rev Med* **31**, 15–27.

17 Hall JE, Guyton AC, Smith MJ Jr & Coleman TG (1980) Blood pressure and renal function during chronic changes in sodium intake: role of angiotensin. *Am J Physiol* **239**, F271–F280.

18 Hall JE (2016) Renal dysfunction, rather than nonrenal vascular dysfunction, mediates salt-induced hypertension. *Circulation* **133**, 894–906.

19 Morris RC Jr, Schmidlin O, Sebastian A, Tanaka M & Kurtz TW (2016) Vasodysfunction that involves renal vasodysfunction, not abnormally increased renal retention of sodium, accounts for the initiation of salt-induced hypertension. *Circulation* **133**, 881–893.

20 Kurtz TW, DiCarlo SE, Pravenec M, Schmidlin O, Tanaka M & Morris RC Jr (2016) An alternative hypothesis to the widely held view that renal excretion of sodium accounts for resistance to salt-induced hypertension. *Kidney Int* **90**, 965–973.

21 Kurtz TW, DiCarlo SE, Pravenec M, Ježek F, Šilar J, Kofránek J & Morris RC Jr (2018) Testing computer models predicting human responses to a high-salt diet. *Hypertension* **72**, 1407–1416.

22 Gensalt (2007) GenSalt: rationale, design, methods and baseline characteristics of study participants. *J Hum Hypertens* **21**, 639–646.

23 Weinberger MH, Stegner JE & Fineberg NS (1993) A comparison of two tests for the assessment of blood pressure responses to sodium. *Am J Hypertens* **6**, 179–184.

24 Currie G & Delles C (2016) Use of biomarkers in the evaluation and treatment of hypertensive patients. *Curr Hypertens Rep* **18**, 54.
25 Adler AJ, Taylor F, Martin N, Gottlieb S, Taylor RS & Ebrahim S (2014) Reduced dietary salt for the prevention of cardiovascular disease. *Cochrane Database Syst Rev* **2014**, CD009217.
26 Sanders PW (2009) Vascular consequences of dietary salt intake. *Am J Physiol Renal Physiol* **297**, F237–F243.
27 Farquhar WB, Edwards DG, Jurkovitz CT & Weintraub WS (2015) Dietary sodium and health: more than just blood pressure. *J Am Coll Cardiol* **65**, 1042–1050.
28 Robinson AT, Edwards DG & Farquhar WB (2019) The influence of dietary salt beyond blood pressure. *Curr Hypertens Rep* **21**, 42.
29 Tzemos N, Lim PO, Wong S, Struthers AD & MacDonald TM (2008) Adverse cardiovascular effects of acute salt loading in young normotensive individuals. *Hypertension* **51**, 1525–1530.
30 Greaney JL, DuPont JJ, Lennon-Edwards SL, Sanders PW, Edwards DG & Farquhar WB (2012) Dietary sodium loading impairs microvascular function independent of blood pressure in humans: role of oxidative stress. *J Physiol* **590**, 5519–5528.
31 Dickinson KM, Clifton PM, Burrell LM, Barrett PH & Keogh JB (2014) Postprandial effects of a high salt meal on serum sodium, arterial stiffness, markers of nitric oxide production and markers of endothelial function. *Atherosclerosis* **232**, 211–216.
32 Cavka A, Jukic I, Ali M, Goslawski M, Bian JT, Wang E, Drenjancevic I & Phillips SA (2016) Short-term high salt intake reduces brachial artery and microvascular function in the absence of changes in blood pressure. *J Hypertens* **34**, 676–684.
33 D'Elia L, Galletti F, La Fata E, Sabino P & Strazzullo P (2018) Effect of dietary sodium restriction on arterial stiffness: systematic review and meta-analysis of the randomized controlled trials. *J Hypertens* **36**, 734–743.
34 Perry IJ & Beevers DG (1992) Salt intake and stroke: a possible direct effect. *J Hum Hypertens* **6**, 23–25.
35 Nagata C, Takatsuka N, Shimizu N & Shimizu H (2004) Sodium intake and risk of death from stroke in Japanese men and women. *Stroke* **35**, 1543–1547.
36 Allen LA, Schmidt JR, Thompson CT, Carlson BE, Beard DA & Lombard JH (2019) High salt diet impairs cerebral blood flow regulation via salt-induced angiotensin II suppression. *Microcirculation* **26**, e12518.
37 Carbone L, Johnson KC, Huang Y, Pettinger M, Thomas F, Cauley J, Crandall C, Tinker L, LeBoff MS, Wactawski-Wende J *et al.* (2016) Sodium intake and osteoporosis. Findings from the Women's Health Initiative. *J Clin Endocrinol Metab* **101**, 1414–1421.
38 Jobin K, Müller DN, Jantsch J & Kurts C (2021) Sodium and its manifold impact on our immune system. *Trends Immunol* **42**, 469–479.
39 Rakova N, Juttner K, Dahlmann A, Schroder A, Linz P, Kopp C, Rauh M, Goller U, Beck L, Agureev A *et al.* (2013) Long-term space flight simulation reveals infradian rhythmicity in human Na(+) balance. *Cell Metab* **17**, 125–131.
40 Ortiz-Melo D & Coffman TM (2013) A trip to inner space: insights into salt balance from cosmonauts. *Cell Metab* **17**, 1–2.
41 Rakova N, Kitada K, Lerchl K, Dahlmann A, Birukov A, Daub S, Kopp C, Pedchenko T, Zhang Y, Beck L *et al.* (2017) Increased salt consumption induces body water conservation and decreases fluid intake. *J Clin Investig* **127**, 1932–1943.
42 Kitada K, Daub S, Zhang Y, Klein JD, Nakano D, Pedchenko T, Lantier L, LaRocque LM, Marton A, Neubert P *et al.* (2017) High salt intake reprioritizes osmolyte and energy metabolism for body fluid conservation. *J Clin Investig* **127**, 1944–1959.
43 Rossitto G, Maiolino G, Lerco S, Ceolotto G, Blackburn G, Mary S, Antonelli G, Berton C, Bisogni V, Cesari M *et al.* (2020) High sodium intake, glomerular hyperfiltration and protein catabolism in patients with essential hypertension. *Cardiovasc Res* **117**, 1372–1381.
44 Rossi GP (2019) Primary aldosteronism: JACC state-of-the-art review. *J Am Coll Cardiol* **74**, 2799–2811.
45 Hall JE, Granger JP, Smith MJ Jr & Premen AJ (1984) Role of renal hemodynamics and arterial pressure in aldosterone "escape". *Hypertension* **6**, I183–I192.
46 Morisawa N, Kitada K, Fujisawa Y, Nakano D, Yamazaki D, Kobuchi S, Li L, Zhang Y, Morikawa T, Konishi Y *et al.* (2020) Renal sympathetic nerve activity regulates cardiovascular energy expenditure in rats fed high salt. *Hypertens Res* **43**, 482–491.
47 Juraschek SP, Miller ER 3rd, Chang AR, Anderson CAM, Hall JE & Appel LJ (2020) Effects of sodium reduction on energy, metabolism, weight, thirst, and urine volume: results from the DASH (Dietary Approaches to Stop Hypertension)-Sodium Trial. *Hypertension* **75**, 723–729.
48 Jones DW, Luft FC, Whelton PK, Alderman MH, Hall JE, Peterson ED, Califf RM & McCarron DA (2018) Can we end the salt wars with a randomized clinical trial in a controlled environment? *Hypertension* **72**, 10–11.
49 Sattar N, Gill JMR & Alazawi W (2020) Improving prevention strategies for cardiometabolic disease. *Nat Med* **26**, 320–325.
50 Ma Y, He FJ & MacGregor GA (2015) High salt intake: independent risk factor for obesity? *Hypertension* **66**, 843–849.

51 Srikanthan P, Hevener AL & Karlamangla AS (2010) Sarcopenia exacerbates obesity-associated insulin resistance and dysglycemia: findings from the National Health and Nutrition Examination Survey III. *PLoS One* **5**, e10805.

52 Bray GA, Smith SR, de Jonge L, Xie H, Rood J, Martin CK, Most M, Brock C, Mancuso S & Redman LM (2012) Effect of dietary protein content on weight gain, energy expenditure, and body composition during overeating: a randomized controlled trial. *JAMA* **307**, 47–55.

53 Cannon WB (1929) Organization for physiological homeostasis. *Physiol Rev* **9**, 399–431.

54 Guyton AC (1991) Blood pressure control–special role of the kidneys and body fluids. *Science* **252**, 1813–1816.

55 Heer M, Baisch F, Kropp J, Gerzer R & Drummer C (2000) High dietary sodium chloride consumption may not induce body fluid retention in humans. *Am J Physiol Renal Physiol* **278**, F585–F595.

56 Titze J, Krause H, Hecht H, Dietsch P, Rittweger J, Lang R, Kirsch KA & Hilgers KF (2002) Reduced osmotically inactive Na storage capacity and hypertension in the Dahl model. *Am J Physiol Renal Physiol* **283**, F134–F141.

57 Titze J, Lang R, Ilies C, Schwind KH, Kirsch KA, Dietsch P, Luft FC & Hilgers KF (2003) Osmotically inactive skin Na+ storage in rats. *Am J Physiol Renal Physiol* **285**, F1108–F1117.

58 Titze J, Bauer K, Schafflhuber M, Dietsch P, Lang R, Schwind KH, Luft FC, Eckardt KU & Hilgers KF (2005) Internal sodium balance in DOCA-salt rats: a body composition study. *Am J Physiol Renal Physiol* **289**, F793–F802.

59 Titze J, Shakibaei M, Schafflhuber M, Schulze-Tanzil G, Porst M, Schwind KH, Dietsch P & Hilgers KF (2004) Glycosaminoglycan polymerization may enable osmotically inactive Na+ storage in the skin. *Am J Physiol Heart Circ Physiol* **287**, H203–H208.

60 Machnik A, Neuhofer W, Jantsch J, Dahlmann A, Tammela T, Machura K, Park JK, Beck FX, Muller DN, Derer W *et al*. (2009) Macrophages regulate salt-dependent volume and blood pressure by a vascular endothelial growth factor-C-dependent buffering mechanism. *Nat Med* **15**, 545–552.

61 Wiig H, Schroder A, Neuhofer W, Jantsch J, Kopp C, Karlsen TV, Boschmann M, Goss J, Bry M, Rakova N *et al*. (2013) Immune cells control skin lymphatic electrolyte homeostasis and blood pressure. *J Clin Investig* **123**, 2803–2815.

62 Karlsen TV, Nikpey E, Han J, Reikvam T, Rakova N, Castorena-Gonzalez JA, Davis MJ, Titze JM, Tenstad O & Wiig H (2018) High-salt diet causes expansion of the lymphatic network and increased lymph flow in skin and muscle of rats. *Arterioscler Thromb Vasc Biol* **38**, 2054–2064.

63 Kopp C, Linz P, Wachsmuth L, Dahlmann A, Horbach T, Schofl C, Renz W, Santoro D, Niendorf T, Muller DN *et al*. (2012) (23)Na magnetic resonance imaging of tissue sodium. *Hypertension* **59**, 167–172.

64 Kopp C, Linz P, Dahlmann A, Hammon M, Jantsch J, Muller DN, Schmieder RE, Cavallaro A, Eckardt KU, Uder M *et al*. (2013) 23Na magnetic resonance imaging-determined tissue sodium in healthy subjects and hypertensive patients. *Hypertension* **61**, 635–640.

65 Karg MV, Bosch A, Kannenkeril D, Striepe K, Ott C, Schneider MP, Boemke-Zelch F, Linz P, Nagel AM, Titze J *et al*. (2018) SGLT-2-inhibition with dapagliflozin reduces tissue sodium content: a randomised controlled trial. *Cardiovasc Diabetol* **17**, 5.

66 Schneider MP, Raff U, Kopp C, Scheppach JB, Toncar S, Wanner C, Schlieper G, Saritas T, Floege J, Schmid M *et al*. (2017) Skin sodium concentration correlates with left ventricular hypertrophy in CKD. *J Am Soc Nephrol* **28**, 1867–1876.

67 Hammon M, Grossmann S, Linz P, Kopp C, Dahlmann A, Garlichs C, Janka R, Cavallaro A, Luft FC, Uder M *et al*. (2015) 23Na magnetic resonance imaging of the lower leg of acute heart failure patients during diuretic treatment. *PLoS One* **10**, e0141336.

68 Kopp C, Beyer C, Linz P, Dahlmann A, Hammon M, Jantsch J, Neubert P, Rosenhauer D, Muller DN, Cavallaro A *et al*. (2017) Na+ deposition in the fibrotic skin of systemic sclerosis patients detected by 23Na-magnetic resonance imaging. *Rheumatology (Oxford)* **56**, 556–560.

69 Jantsch J, Schatz V, Friedrich D, Schroder A, Kopp C, Siegert I, Maronna A, Wendelborn D, Linz P, Binger KJ *et al*. (2015) Cutaneous Na+ storage strengthens the antimicrobial barrier function of the skin and boosts macrophage-driven host defense. *Cell Metab* **21**, 493–501.

70 Christa M, Weng AM, Geier B, Wörmann C, Scheffler A, Lehmann L, Oberberger J, Kraus BJ, Hahner S, Störk S *et al*. (2019) Increased myocardial sodium signal intensity in Conn's syndrome detected by 23Na magnetic resonance imaging. *Eur Heart J Cardiovasc Imaging* **20**, 263–270.

71 Rossitto G, Mary S, Chen JY, Boder P, Chew KS, Neves KB, Alves RL, Montezano AC, Welsh P, Petrie MC *et al*. (2020) Tissue sodium excess is not hypertonic and reflects extracellular volume expansion. *Nat Commun* **11**, 4222.

72 Lowry OH & Hastings AB (1942) Histochemical changes associated with aging: I. Methods and calculations. *J Biol Chem* **143**, 257–269.

73 Lowry OH, Hastings AB, Hull TZ & Brown AN (1942) Histochemical changes associated with aging: II.

Skeletal and cardiac muscle in rats. *J Biol Chem* **143**, 271–280.
74 Lowry OH, Hastings AB, McCay CN & Brown AN (1946) Histochemical changes associated with aging; liver, brain, and kidney in the rat. *J Gerontol* **1**, 345–357.
75 Rossitto G, Touyz RM, Petrie MC & Delles C (2018) Much Ado about Natrium: modelling tissue sodium as a highly sensitive marker of subclinical and localized oedema. *Clin Sci (Lond)* **132**, 2609–2613.
76 Hofmeister LH, Perisic S & Titze J (2015) Tissue sodium storage: evidence for kidney-like extrarenal countercurrent systems? *Pflugers Arch* **467**, 551–558.
77 Chachaj A, Puła B, Chabowski M, Grzegrzółka J, Szahidewicz-Krupska E, Karczewski M, Janczak D, Dzięgiel P, Podhorska-Okołów M, Mazur G *et al.* (2018) Role of the lymphatic system in the pathogenesis of hypertension in humans. *Lymphat Res Biol* **16**, 140–146.
78 Nikpey E, Karlsen TV, Rakova N, Titze JM, Tenstad O & Wiig H (2017) High-salt diet causes osmotic gradients and hyperosmolality in skin without affecting interstitial fluid and lymph. *Hypertension* **69**, 660–668.
79 Bay J, Kohlhaas M & Maack C (2013) Intracellular Na^+ and cardiac metabolism. *J Mol Cell Cardiol* **61**, 20–27.
80 Aksentijević D, Karlstaedt A, Basalay MV, O'Brien BA, Sanchez-Tatay D, Eminaga S, Thakker A, Tennant DA, Fuller W, Eykyn TR *et al.* (2020) Intracellular sodium elevation reprograms cardiac metabolism. *Nat Commun* **11**, 4337.
81 Hernansanz-Agustín P, Choya-Foces C, Carregal-Romero S, Ramos E, Oliva T, Villa-Piña T, Moreno L, Izquierdo-Álvarez A, Cabrera-García JD, Cortés A *et al.* (2020) Na(+) controls hypoxic signalling by the mitochondrial respiratory chain. *Nature* **586**, 287–291.
82 Geisberger S, Bartolomaeus H, Neubert P, Willebrand R, Zasada C, Bartolomaeus T, McParland V, Swinnen D, Geuzens A, Maifeld A *et al.* (2021) Salt transiently inhibits mitochondrial energetics in mononuclear phagocytes. *Circulation* **144**, 144–158.
83 Fischereder M, Michalke B, Schmöckel E, Habicht A, Kunisch R, Pavelic I, Szabados B, Schönermarck U, Nelson PJ & Stangl M (2017) Sodium storage in human tissues is mediated by glycosaminoglycan expression. *Am J Physiol Renal Physiol* **313**, F319–F325.
84 Nijst P, Olinevich M, Hilkens P, Martens P, Dupont M, Tang WHW, Lambrichts I, Noben JP & Mullens W (2018) Dermal interstitial alterations in patients with heart failure and reduced ejection fraction: a potential contributor to fluid accumulation? *Circ Heart Fail* **11**, e004763.
85 Issue S (2019) Extracellular matrix in health and disease. *FEBS J* **286**, 2823–3075.
86 Humphrey JD, Dufresne ER & Schwartz MA (2014) Mechanotransduction and extracellular matrix homeostasis. *Nat Rev Mol Cell Biol* **15**, 802–812.
87 Tschumperlin DJ, Ligresti G, Hilscher MB & Shah VH (2018) Mechanosensing and fibrosis. *J Clin Investig* **128**, 74–84.
88 Wiig H, Luft FC & Titze JM (2018) The interstitium conducts extrarenal storage of sodium and represents a third compartment essential for extracellular volume and blood pressure homeostasis. *Acta Physiol (Oxf)* **222**, e13006.
89 Laffer CL, Scott RC 3rd, Titze JM, Luft FC & Elijovich F (2016) Hemodynamics and salt-and-water balance link sodium storage and vascular dysfunction in salt-sensitive subjects. *Hypertension* **68**, 195–203.
90 Braconnier P, Milani B, Loncle N, Lourenco JM, Brito W, Delacoste J, Maillard M, Stuber M, Burnier M & Pruijm M (2020) Short-term changes in dietary sodium intake influence sweat sodium concentration and muscle sodium content in healthy individuals. *J Hypertens* **38**, 159–166.
91 Chen JY (2020) Abstracts from the 2020 Annual Scientific Meeting of the British and Irish Hypertension Society (BIHS); O-04. *J Hum Hypertens* **34**, 3.
92 Wild J, Jung R, Knopp T, Efentakis P, Benaki D, Grill A, Wegner J, Molitor M, Garlapati V, Rakova N *et al.* (2021) Aestivation motifs explain hypertension and muscle mass loss in mice with psoriatic skin barrier defect. *Acta Physiol (Oxf)* **232**, e13628.
93 Miyakawa H, Woo SK, Dahl SC, Handler JS & Kwon HM (1999) Tonicity-responsive enhancer binding protein, a rel-like protein that stimulates transcription in response to hypertonicity. *Proc Natl Acad Sci USA* **96**, 2538–2542.
94 Choi SY, Lee-Kwon W & Kwon HM (2020) The evolving role of TonEBP as an immunometabolic stress protein. *Nat Rev Nephrol* **16**, 352–364.
95 Tarazi RC, Frohlich ED & Dustan HP (1968) Plasma volume in men with essential hypertension. *N Engl J Med* **278**, 762–765.
96 Tarazi RC, Dustan HP & Frohlich ED (1969) Relation of plasma to interstitial fluid volume in essential hypertension. *Circulation* **40**, 357–366.
97 Pfeffer MA, Shah AM & Borlaug BA (2019) Heart failure with preserved ejection fraction in perspective. *Circ Res* **124**, 1598–1617.
98 Boorsma EM, Ter Maaten JM, Damman K, Dinh W, Gustafsson F, Goldsmith S, Burkhoff D, Zannad F, Udelson JE & Voors AA (2020) Congestion in heart failure: a contemporary look at physiology, diagnosis and treatment. *Nat Rev Cardiol* **17**, 641–655.
99 Dongaonkar RM, Stewart RH, Geissler HJ & Laine GA (2010) Myocardial microvascular permeability,

interstitial oedema, and compromised cardiac function. *Cardiovasc Res* **87**, 331–339.
100 Tobian L Jr & Binion JT (1952) Tissue cations and water in arterial hypertension. *Circulation* **5**, 754–758.
101 Zelis R, Delea CS, Coleman HN & Mason DT (1970) Arterial sodium content in experimental congestive heart failure. *Circulation* **41**, 213–216.
102 Herring NPDJ (2018) Levick's Introduction to Cardiovascular Physiology, 6th edn. CRC Press Book, Boca Raton, FL.
103 Levick JR & Michel CC (2010) Microvascular fluid exchange and the revised Starling principle. *Cardiovasc Res* **87**, 198–210.
104 Lewis JC, Taylor RG, Jones ND, St Clair RW & Cornhill JF (1982) Endothelial surface characteristics in pigeon coronary artery atherosclerosis. I. Cellular alterations during the initial stages of dietary cholesterol challenge. *Lab Invest* **46**, 123–138.
105 Gouverneur M, Spaan JA, Pannekoek H, Fontijn RD & Vink H (2006) Fluid shear stress stimulates incorporation of hyaluronan into endothelial cell glycocalyx. *Am J Physiol Heart Circ Physiol* **290**, H458–H462.
106 Wang G, Kostidis S, Tiemeier GL, Sol W, de Vries MR, Giera M, Carmeliet P, van den Berg BM & Rabelink TJ (2020) Shear stress regulation of endothelial glycocalyx structure is determined by glucobiosynthesis. *Arterioscler Thromb Vasc Biol* **40**, 350–364.
107 Wenstedt EFE, Olde Engberink RHG & Vogt L (2018) Sodium handling by the blood vessel wall: critical for hypertension development. *Hypertension* **71**, 990–996.
108 Broekhuizen LN, Lemkes BA, Mooij HL, Meuwese MC, Verberne H, Holleman F, Schlingemann RO, Nieuwdorp M, Stroes ES & Vink H (2010) Effect of sulodexide on endothelial glycocalyx and vascular permeability in patients with type 2 diabetes mellitus. *Diabetologia* **53**, 2646–2655.
109 Vlahu CA, Lemkes BA, Struijk DG, Koopman MG, Krediet RT & Vink H (2012) Damage of the endothelial glycocalyx in dialysis patients. *J Am Soc Nephrol* **23**, 1900–1908.
110 Song JW, Zullo JA, Liveris D, Dragovich M, Zhang XF & Goligorsky MS (2017) Therapeutic restoration of endothelial glycocalyx in sepsis. *J Pharmacol Exp Ther* **361**, 115–121.
111 Olde Engberink RH, Rorije NM, Homan van der Heide JJ, van den Born BJ & Vogt L (2015) Role of the vascular wall in sodium homeostasis and salt sensitivity. *J Am Soc Nephrol* **26**, 777–783.
112 Oberleithner H, Peters W, Kusche-Vihrog K, Korte S, Schillers H, Kliche K & Oberleithner K (2011) Salt overload damages the glycocalyx sodium barrier of vascular endothelium. *Pflugers Arch* **462**, 519–528.
113 Oberleithner H, Riethmüller C, Schillers H, MacGregor GA, de Wardener HE & Hausberg M (2007) Plasma sodium stiffens vascular endothelium and reduces nitric oxide release. *Proc Natl Acad Sci USA* **104**, 16281–16286.
114 Petrova TV & Koh GY (2020) Biological functions of lymphatic vessels. *Science* **369**, eaax4063.
115 Scallan JP, Zawieja SD, Castorena-Gonzalez JA & Davis MJ (2016) Lymphatic pumping: mechanics, mechanisms and malfunction. *J Physiol* **594**, 5749–5768.
116 Rossitto G, Sneddon M & Rockson SG (2019) The lymphatic system. In Textbook of Vascular Medicine (Touyz RM & Delles C, eds), pp. 45–57. Springer International Publishing, Cham.
117 Scallan JP, Wolpers JH, Muthuchamy M, Zawieja DC, Gashev AA & Davis MJ (2012) Independent and interactive effects of preload and afterload on the pump function of the isolated lymphangion. *Am J Physiol Heart Circ Physiol* **303**, H809–H824.
118 Davis MJ, Scallan JP, Wolpers JH, Muthuchamy M, Gashev AA & Zawieja DC (2012) Intrinsic increase in lymphangion muscle contractility in response to elevated afterload. *Am J Physiol Heart Circ Physiol* **303**, H795–H808.
119 Lankhorst S, Severs D, Markó L, Rakova N, Titze J, Müller DN, Danser AH & van den Meiracker AH (2017) Salt sensitivity of angiogenesis inhibition-induced blood pressure rise: role of interstitial sodium accumulation? *Hypertension* **69**, 919–926.
120 Scherer C, Pfisterer L, Wagner AH, Hodebeck M, Cattaruzza M, Hecker M & Korff T (2014) Arterial wall stress controls NFAT5 activity in vascular smooth muscle cells. *J Am Heart Assoc* **3**, e000626.
121 Yang GH, Zhou X, Ji WJ, Zeng S, Dong Y, Tian L, Bi Y, Guo ZZ, Gao F, Chen H *et al.* (2014) Overexpression of VEGF-C attenuates chronic high salt intake-induced left ventricular maladaptive remodeling in spontaneously hypertensive rats. *Am J Physiol Heart Circ Physiol* **306**, H598–H609.
122 Lopez Gelston CA, Balasubbramanian D, Abouelkheir GR, Lopez AH, Hudson KR, Johnson ER, Muthuchamy M, Mitchell BM & Rutkowski JM (2018) Enhancing renal lymphatic expansion prevents hypertension in mice. *Circ Res* **122**, 1094–1101.
123 Balasubbramanian D, Baranwal G, Clark MC, Goodlett BL, Mitchell BM & Rutkowski JM (2020) Kidney-specific lymphangiogenesis increases sodium excretion and lowers blood pressure in mice. *J Hypertens* **38**, 874–885.
124 Balasubbramanian D, Gelston CAL, Lopez AH, Iskander G, Tate W, Holderness H, Rutkowski JM & Mitchell BM (2020) Augmenting renal lymphatic density prevents angiotensin II-induced hypertension in male and female mice. *Am J Hypertens* **33**, 61–69.

125 Henri O, Pouehe C, Houssari M, Galas L, Nicol L, Edwards-Levy F, Henry JP, Dumesnil A, Boukhalfa I, Banquet S *et al*. (2016) Selective stimulation of cardiac lymphangiogenesis reduces myocardial edema and fibrosis leading to improved cardiac function following myocardial infarction. *Circulation* **133**, 1484–1497; discussion 1497.
126 Aspelund A, Robciuc MR, Karaman S, Makinen T & Alitalo K (2016) Lymphatic system in cardiovascular medicine. *Circ Res* **118**, 515–530.
127 Escobedo N & Oliver G (2017) The lymphatic vasculature: its role in adipose metabolism and obesity. *Cell Metab* **26**, 598–609.
128 Oliver G, Kipnis J, Randolph GJ & Harvey NL (2020) The lymphatic vasculature in the 21(st) century: novel functional roles in homeostasis and disease. *Cell* **182**, 270–296.
129 Mortimer PS & Rockson SG (2014) New developments in clinical aspects of lymphatic disease. *J Clin Investig* **124**, 915–921.
130 Rossitto G, Mary S, McAllister C, Neves KB, Haddow L, Rocchiccioli JP, Lang NN, Murphy CL, Touyz RM, Petrie MC *et al*. (2020) Reduced lymphatic reserve in heart failure with preserved ejection fraction. *J Am Coll Cardiol* **76**, 2817–2829.
131 Wilck N, Balogh A, Markó L, Bartolomaeus H & Müller DN (2019) The role of sodium in modulating immune cell function. *Nat Rev Nephrol* **15**, 546–558.
132 Zhang WC, Zheng XJ, Du LJ, Sun JY, Shen ZX, Shi C, Sun S, Zhang Z, Chen XQ, Qin M *et al*. (2015) High salt primes a specific activation state of macrophages, M(Na). *Cell Res* **25**, 893–910.
133 Kleinewietfeld M, Manzel A, Titze J, Kvakan H, Yosef N, Linker RA, Muller DN & Hafler DA (2013) Sodium chloride drives autoimmune disease by the induction of pathogenic TH17 cells. *Nature* **496**, 518–522.
134 Binger KJ, Gebhardt M, Heinig M, Rintisch C, Schroeder A, Neuhofer W, Hilgers K, Manzel A, Schwartz C, Kleinewietfeld M *et al*. (2015) High salt reduces the activation of IL-4- and IL-13-stimulated macrophages. *J Clin Investig* **125**, 4223–4238.
135 Hernandez AL, Kitz A, Wu C, Lowther DE, Rodriguez DM, Vudattu N, Deng S, Herold KC, Kuchroo VK, Kleinewietfeld M *et al*. (2015) Sodium chloride inhibits the suppressive function of FOXP3+ regulatory T cells. *J Clin Investig* **125**, 4212–4222.
136 Barbaro NR, Foss JD, Kryshtal DO, Tsyba N, Kumaresan S, Xiao L, Mernaugh RL, Itani HA, Loperena R, Chen W *et al*. (2017) Dendritic cell amiloride-sensitive channels mediate sodium-induced inflammation and hypertension. *Cell Rep* **21**, 1009–1020.
137 Van Beusecum JP, Barbaro NR, McDowell Z, Aden LA, Xiao L, Pandey AK, Itani HA, Himmel LE, Harrison DG & Kirabo A (2019) High salt activates CD11c(+) antigen-presenting cells via SGK (serum glucocorticoid kinase) 1 to promote renal inflammation and salt-sensitive hypertension. *Hypertension* **74**, 555–563.
138 Berry MR, Mathews RJ, Ferdinand JR, Jing C, Loudon KW, Wlodek E, Dennison TW, Kuper C, Neuhofer W & Clatworthy MR (2017) Renal sodium gradient orchestrates a dynamic antibacterial defense zone. *Cell* **170**, 860–874.e19.
139 Neubert P, Homann A, Wendelborn D, Bär AL, Krampert L, Trum M, Schröder A, Ebner S, Weichselbaum A, Schatz V *et al*. (2020) NCX1 represents an ionic Na+ sensing mechanism in macrophages. *PLoS Biol* **18**, e3000722.
140 Constantinescu AA, Vink H & Spaan JA (2003) Endothelial cell glycocalyx modulates immobilization of leukocytes at the endothelial surface. *Arterioscler Thromb Vasc Biol* **23**, 1541–1547.
141 Schaefer A & Hordijk PL (2015) Cell-stiffness-induced mechanosignaling – a key driver of leukocyte transendothelial migration. *J Cell Sci* **128**, 2221–2230.
142 McDonald KK, Cooper S, Danielzak L & Leask RL (2016) Glycocalyx degradation induces a proinflammatory phenotype and increased leukocyte adhesion in cultured endothelial cells under flow. *PLoS One* **11**, e0167576.
143 Dasinger JH, Alsheikh AJ, Abais-Battad JM, Pan X, Fehrenbach DJ, Lund H, Roberts ML, Cowley AW Jr, Kidambi S, Kotchen TA *et al*. (2020) Epigenetic modifications in T cells: the role of DNA methylation in salt-sensitive hypertension. *Hypertension* **75**, 372–382.
144 Abais-Battad JM, Alsheikh AJ, Pan X, Fehrenbach DJ, Dasinger JH, Lund H, Roberts ML, Kriegel AJ, Cowley AW Jr, Kidambi S *et al*. (2019) Dietary effects on dahl salt-sensitive hypertension, renal damage, and the T lymphocyte transcriptome. *Hypertension* **74**, 854–863.
145 Olde Engberink RHG, Selvarajah V & Vogt L (2020) Clinical impact of tissue sodium storage. *Pediatr Nephrol* **35**, 1373–1380.