Effects of acid-base imbalance on vascular reactivity

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Acid-base homeostasis maintains systemic arterial pH within a narrow range. Whereas the normal range of pH for clinical laboratories is 7.35-7.45, in vivo pH is maintained within a much narrower range. This degree of tight regulation is accomplished by chemical buffering in extracellular and intracellular fluids and regulatory responses that are controlled by the respiratory and renal systems. Changes in pH can have profound, yet poorly understood, influence on pulmonary and systemic vascular resistance and reactivity to pressor agents.

Changes in pH can be divided into those occurring in the extracellular space (pH_o) and those occurring within the intracellular space (pH_i), although, extracellular and intracellular compartments influence each other. Cell studies have shown that changes in pH_o cause only small and slow changes in pH_i; as a result, pH_o and pH_i have usually been considered separately (1). For example, in cardiac myocytes the change in pH_i was only around 30% of the pH_o change and occurred slowly (10-40 min) (2,3). However, in rat mesenteric resistance vessels the situation is different; changes in pH_o cause large (70% pH_o changes) and rapid (<2 min) changes in pH_i (4). Therefore, it appears that not all vascular smooth muscles behave in a similar manner when pH_o is changed, which may be a consequence of differing permeabilities to protons or mechanisms of regulating pH_i.

Consistent with the multiple events involved in the changes in tone produced by altered pH_o, including type of vascular bed, several factors and mechanisms, in addition to hydrogen ion concentration, have been suggested to be involved. The scientific literature has many reports concerning acid-base balance and endothelium function, but these concepts are not clear about acid-base disorders and their relations with the three known mechanisms of endothelium-dependent vascular reactivity: nitric oxide (NO/cGMP-dependent), prostacyclin (PGI_2/cAMP-dependent) and hyperpolarization. During the last decades, many studies have been published and have given rise to confronting data on acid-base disorder and endothelial function. Therefore, the main proposal of this review is to provide a critical analysis of the state of art and incentivize researchers to develop more studies about these issues.

Key words: Acid-base balance; Nitric oxide; Vascular reactivity; Endothelium; Alkalosis; Acidosis

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Introduction

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Changes in pH can be divided into those occurring in the extracellular space (pH_o) and those occurring within the intracellular space (pH_i), although, extracellular and intracellular compartments influence each other. Cell studies have shown that changes in pH_o cause only small and slow changes in pH_i; as a result, pH_o and pH_i have usually been considered separately (1). For example, in cardiac myocytes the change in pH_i was only around 30% of the pH_o change and occurred slowly (10-40 min) (2,3). However, in rat mesenteric resistance vessels the situation is different; changes in pH_o cause large (70% pH_o changes) and rapid (<2 min) changes in pH_i (4). Therefore, it appears that not all vascular smooth muscles behave in a similar manner when pH_o is changed, which may be a consequence of differing permeabilities to protons or mechanisms of regulating pH_i.

Consistent with the multiple events involved in the changes in tone produced by altered pH_o, including type of
vascular bed, several factors and mechanisms, in addition to hydrogen ion concentration, have been suggested to be involved. Prostanoids, purines, sensory neuro-transmitters (5-7), hyperpolarization, and changes in intracellular calcium concentration ([Ca^{2+}]i) are candidates as well as the recently demonstrated vasoactive molecule nitric oxide (NO) (5). The most common manner to study NO action has been to interfere with the enzymatic production of this gas and the same experimental approach has been used in studies involving NO and metabolic vasodilation (8-10).

There are many reports concerning acid-base imbalance and endothelium function, but these concepts are, in general, too specific. The effects of pH and its mechanism of action may be expected to vary between vessel types. The effects of pH may alter with time or separate acute and chronic pathways may be evoked. The endothelium may well activate a different pathway from that of the smooth muscle and extracellular matrix and there is extensive literature on the important role played by the endothelium in mediating vascular responsiveness. This review analyzes how vascular tone can be regulated by endothelial and smooth muscle function under the influence of changes of pH.

Effect of pHo on pHi

In vitro studies about the measurement of pHo are generally simple, occurring in perfusate; however, the measurement of pHi is problematic and publications did not appear until the 1980’s. This was because there was no suitable technique for measuring pHi in small, contractile preparations. Presently, two main techniques are available: magnetic resonance and fluorescent indicators (using 2’7’-bis-carboxyethyl-5(6)-carboxyfluorescein (BCECF) and 5-(and-6)-carboxy SNARF®-1, acetoxymethyl ester, acetate).

Low pH values induce vessel dilation. When extracellular pH is 7.4, the corresponding intracellular value is 7.1 to 7.2 when actually it should be 6.4. This implies that protons are actively extruded from the cells against an electrochemical gradient (11-13). The main proton transporters are the Na+/H+ exchanger and the sodium coupled bicarbonate. The type 1 Na+/H+ isoform is localized in the vascular smooth muscle and can be activated by vasoconstrictors and growth factors, glucose, and hyperosmotic stress leading to increased rate of acid recovery, increased influx of sodium and restoration of cell volume. It is likely that intracellular concentration of calcium modulates the activation of this transporter, as well as a mechanism dependent on or independent of protein kinase C. Likewise, cGMP has also been implicated in the control of the exchange activity as a result of pH alterations. Unlike the Na+/H+ transporter, the Na+/HCO3- exchanger may vary between smooth muscles. It appears that this exchanger has a plethora of different expressions and the exact physiological importance of each is challenging. The consensus is that this transporter accounts for a significant role in the control of pHi, except for the guinea pig femoral artery where it has a very small fraction of acid extrusion. Additionally, there is a very consistent finding that smooth muscles have an Na+-independent Cl-/HCO3- exchange pathway that has been shown in cultured and intact vascular preparations (14-16).

It is possible that the response to low pHo values is mediated through the decrease in pHi. Furthermore, most intracellular biochemical reactions of excitation-contraction coupling are potentially affected by low pH and often in the direction that favors relaxation. On the other hand, in most vascular beds, the immediate response to a selective decrease in pHi is increased tension and some may respond with acute alkalization, which may cause paradoxical relaxation of an agonist-induced response or have little effect on vascular tone. Thus, reduction of extracellular pH is probably more important for vasodilation than the associated reduction in pHi. It is becoming clear that the reduction of [Ca^{2+}]i is involved significantly, although the role of membrane potential is not yet understood (14).

Control of vascular smooth muscle by external stimuli involves the generation of intracellular H+ signals, which are transduced by the concerted action of a variety of cellular H+ sensors. Intracellular pH sensors form signal complexes, which are able to convert H+ signals to intracellular Ca^{2+} signals thereby enabling both homeostatic responses to acidosis and alkalosis as well as control of smooth muscle function (17).

Respiratory acidosis

The pH has marked effects on the blood flow of several vascular beds but the underlying mechanisms are incompletely understood. It is still not agreed, for example, whether it is the fall in pHo or pHi that is responsible for changes in tone resulting from hypercapnic acidosis. This issue has been further complicated by the recent discovery that NO may also be involved in vasodilator responses to hypercapnia. This finding has led some laboratories to divert attention away from vascular smooth muscle.

The role of NO is best investigated in the cerebral circulation where it plays an important role in modulating response to acidosis, and where it is probably of extravascular origin (6). Several studies have shown increased
coronary blood flow during hypercapnia (18,19). Whether 
P_{CO_2} or pH exerts a direct effect on the smooth muscle of 
coronary vessels or whether the vascular response is 
mediated through other mechanisms is currently not known.

NO was proposed as a mediator of hypercapnia-evoked 
coronary vasodilation in the in situ dog heart (20) and 
findings in isolated aortic strips suggest that vasorelaxa-
tion in this artery in response to CO₂ may be partially 
mediated by NO (21). A number of publications have 
implicated NO in the vasodilatory response of the cerebral 
vasculature to hypercapnia (22), although more recent 
evidence suggests that the role of NO may be “permissive” 
rather than “causative” in this vascular bed (23).

Evidence from studying in situ dog hearts (20) came 
primarily from experiments in which the dilatory effects 
of hypercapnia on the coronary microvessels were attenuated 
(though not abolished) by prior exposure to the NO syn-
thase (NOS) inhibitors L-NAME and L-NMMA. Further-
more, the coronary hypercapneic-induced vasodilation 
component that was sensitive to NOS inhibition was not 
secondary to increased blood flow, indicating that the re-
lease of NO was likely due to a direct effect of CO₂ (or H⁺) on 
the vascular endothelium rather than to a shear stress-
induced increase of coronary flow rate. No effect of the NOS 
inhibitors was observed on basal coronary flow, excluding 
the role of NO in the regulation of basal coronary vascular 
tone. This observation conflicts with in vitro findings in guin-
ea pig Langendorff heart preparations, in which NOS inhibi-
tion reduced basal coronary vascular flow (21-23).

The role of NO in rat coronary flow regulation during 
acidosis was evaluated in isolated perfused rat Langen-
dorff heart preparations exposed to brief periods of hyper-
capnic acidosis. Respiratory acidosis resulted in increased 
coronary flow, in conjunction with decreased contractile 
tension. Heart rate remained unaltered. The NOS inhibitor, 
L-NAME (100 µM), failed to attenuate the increases in 
coronary flow during hypercapnia or metabolic acidosis, 
even though it significantly reduced basal flow. These 
results suggest that, although NO contributes to the regu-
lation of basal coronary vascular tone, it is not a mediator of 
the vasodilatory effects of hypercapnia and acidosis in 
this type of preparation (24).

Hypercapnia evokes responses that are both NO de-
pendent and independent. One possible mechanism is 
hypercapnia-induced NO production via the L-arginine/ 
NO pathway. However, NO donor restores the response to 
hypercapnia after prior attenuation with L-NAME. This 
would suggest that the production of NO may not be 
increased during hypercapnia and that the role of NO is 
merely permissive for the direct effect of pH change in 
vascular smooth muscle cells (23).

### Respiratory alkalosis

Hyperoxia and alkalosis produce pulmonary vasodila-
tion independent of endothelium-derived NO in newborn 
lambs; however, their mechanisms of action are unknown 
(25). NO is an important modulator of pulmonary vascular 
tone and produces potent pulmonary vasodilation during 
pulmonary hypertension. *In vitro* evidence suggests that 
NO may mediate the vasodilating effects of oxygen. To 
investigate whether NO synthesis mediates pulmonary 
vasodilation produced by hyperoxia, 100% oxygen normo-
capnic ventilation, arterial oxygen tension >450 torr (60 
kPa) and alkalosis (hyperventilation with 21% oxygen, pH 
>7.55) were studied in 8 intact newborn lambs during similar 
degrees of pulmonary hypertension. It was re-
ported that hyperoxia and alkalosis can produce pulmo-
nary vasodilation independent of NO synthesis in the intact 
newborn lamb with pulmonary hypertensive disorders in-
duced by U-46619 (a thromboxane A2 mimic) or N-omega-
nitro-L-arginine (an inhibitor of NO synthesis) (25).

It has been reported that alkalosis-induced vasodila-
tion is mediated by NO in newborn piglet pulmonary artery 
and vein rings precontracted with U-46619. In contrast, 
prostacyclin or K⁺ channel activation contributed to the 
response of *in situ* pulmonary vessels. A study that sought 
to identify factors contributing to the difference in reactivity 
between isolated and in situ pulmonary vessels found that 
NOS inhibition fully blocked alkalosis-induced relaxation 
of piglet artery and vein rings in isolated pulmonary prepa-
rations ventilated with a gas mixture containing 3% CO₂ 
(pH ~7.6) (26,27). In contrast, NOS inhibition alone had no 
effect on alkalosis-induced pulmonary vasodilation in iso-
lated piglet lungs ventilated with gas mixture containing 0% CO₂ (pH ~7.6) (28). These data indicate that investiga-
tion of other factors, such as perivascular tissue (e.g., 
adventitia and parenchyma) and remote signaling path-
ways, should be carried out to reconcile this discrepancy in 
reactivity between isolated and in situ arteries (29).

Hypocapnic alkalosis-mediated relaxation is signifi-
cantly blunted in piglet pulmonary venous rings without 
fundamental endothelium and in rings treated with NOS or 
guanulate cyclase inhibitor, suggesting that dilation is me-
diated by the NO-cGMP pathway (26) rather than by PGI₂ 
as reported by Hammerman et al. (30). In contrast to piglet 
pulmonary vessels, NO did not contribute to alkalosis-
induced vasodilation in the rabbit (31) or rat (32) lung. PGI₂ 
synthesis, like NO synthesis, is enhanced by increased 
endothelial cell cytosolic Ca²⁺ (33). These findings reflect 
the interspecies differences in dominant endothelium-de-

erived modulator synthesis.

Alkalosis causes a reduction in pulmonary vascular
resistance at normal and elevated tone conditions with the response limited primarily to the small arteries, which is not mediated by NO (32). The effects of alkalosis are abolished when vascular tone was increased with a low dose of KCl, suggesting that vascular response to pH may also involve changes in membrane potential.

**Metabolic acidosis**

For more than a century, it has been known that changes in pH are determinant of tone. Gaskell (34) demonstrated that acid solutions evoke vascular smooth muscle relaxation and more recent studies have shown that reduction of blood pH increases blood flow (35). This phenomenon, the so-called ‘acidic-metabolic vasodilation’, has been suggested to contribute to the regulation of local blood flow, mediating vasodilation that occurs during hypoxia or ischemia or during increased metabolic activity in order to fulfill the need for energy and oxygen.

A well-known phenomenon is that reduction of perivascular pH in acidemia decreases the responsiveness to vasoconstrictors and results in difficulty to maintain systemic blood pressure (36). Perivascular pH can affect many cellular processes (4), but the precise mechanisms of vascular hyporesponsiveness remain uncertain. Low pH has been shown to reduce Ca2+ influx (37), to inhibit myofilament contractility (38) and to alter receptors on the cell surface (39), accounting for the attenuation of vasoconstrictor responses.

Although these actions were observed with relatively large changes in pH, modest acidification (i.e., from pH 7.4 to 7.0) has also been demonstrated to cause substantial inhibition of vascular smooth muscle contractility (40), which has been in part associated with hyperpolarization (41) and an increase in intracellular Ca2+ sequestration. In addition to these direct actions of H+ on smooth muscle, it has been demonstrated that endothelium-derived NO plays an important role in the hyporesponsiveness to vasoconstrictors elicited by acidemia (42).

Hattori et al. (43) examined the effects of modest acidification (pH7, 7.4 to 7.0) on the dilatory responses of isolated rat thoracic aorta and showed that modest acidification increases NO-mediated relaxation in rat aorta, probably due to an enhancement of cGMP-dependent pathway. In an acidic environment, NO seems to be more stable; additionally, relaxation was unrelated to K+ channel mechanisms. NO is also implicated in cerebral arteriolar dilation because this was partially inhibited by L-NMMA and endothelial impairment. There are two possible explanations for endothelial NO-mediated vasodilation: 1) acidosis may activate NOS and 2) acidosis protects spontaneously released NO because NO is stable in acidic media (44).

Acidic vasodilation has mainly been suggested to be endothelium independent, but it is the enzymatically produced NO that has been suggested to be involved, making the origin of this NO unclear. In physiological concentration, nitrite evokes vasodilation, most likely through NO release. This NO release and parallel vasodilation is increased if the environmental pH is lowered to levels normally found in tissues after ischemia/hypoxia or increased metabolic activity. NO formation from nitrite is increased at low pH and acidic vasodilation by nitrite may involve cGMP. However, it is possible that some effects of NO may be related to other mechanisms such as direct interaction with ion channels. This suggests that non-enzymatically derived NO contributes to the “metabolic-acidic” local blood flow regulation in rat aorta (45).

In systemic vessels, acidosis causes vasodilation due to hyperpolarization of smooth muscles and it is possible that a similar potential effect may be present in pulmonary vessels. It has also been reported that acidosis inhibits calcium influx through “leak” channels in endothelial cells (46) and thus may inhibit NO synthesis. Activation of KATP channels and subsequent inhibition of Ca2+ influx via voltage dependent calcium channels is the mechanism by which a decrease in pH (with HCl) produces relaxation in denuded internal mammary artery (47).

Hypercapneic and eucapneic acidosis have different mechanisms between vascular beds. However, both lead to increased hydrogen ion concentration, and the direct and/or indirect effects are related to acidosis-induced dilation via potassium and calcium channels in vascular smooth muscle. Smooth muscle KATP channels along with endothelium KATP channels contribute to acidosis-induced dilation. The activation of potassium channels by low pH is responsible for cell membrane hyperpolarization. Other types of potassium channels (KCa, KIR, Kc) seem to have varied roles in acidosis vasodilation depending on several factors, such as species and organ studied.

Most studies have associated acidosis with vascular dilatation attributed to cell hyperpolarization, decrease of intracellular calcium concentration, activation of potassium channels and NO. Although these may be the most common findings, some investigators have described acidic vasoconstriction in isolated aortas from rats. This indicates that vascular smooth muscle responses to acidic conditions are strain specific. Like strain specificity, the effects of acidosis are vascular-bed specific.

**Metabolic alkalosis**

Investigation of the effect of metabolic alkalosis on the
endothelium-dependent reactivity is rare. One paper mentioning possible effects of metabolic alkalosis relates the important role that NO plays in the transition from intrauterine to extrauterine life. If this transition fails, a condition called persistent pulmonary hypertension of the neonate may develop. The current treatment modalities for this disease include induction of alkalosis by hyperventilation or alkali infusion, inhaled NO and extracorporeal membrane oxygenation (48). During hyperventilation, lower $P_{CO_2}$ values resulted in respiratory alkalosis, relaxed pulmonary vasculature and improved oxygenation. A similar increase in pulmonary blood flow can be obtained by intravenous infusion of alkaline solution that would increase pH by inducing metabolic alkalosis (49). There is evidence from animal studies that the elevated pH rather than the low $P_{CO_2}$ is responsible for the resultant change in vascular resistance (50,51). Nagy et al. (49) examined the effect of pH on the activity and expression of endothelial NOS (eNOS) in cultured bovine aortic endothelial cells as a possible explanation for the pH-dependent drop in pulmonary vascular resistance. They did not observe eNOS expression after short- (4 h) and long-term (16 h) exposure to alkalosis (pH 7.1 to 7.6). Mizuno et al. (52) showed that increased extracellular pH activates eNOS via the influx of extracellular calcium and that the sodium/calcium exchanger regulates eNOS activity during alkalosis, collaborating for sustained activation of eNOS. Extracellular alkalosis is suggested to be involved in the stimulation of NO release via calcium influx. A close relationship exists between calcium uptake into endothelial cells and activation of the Na+/Ca²⁺ exchanger, as well as a tight interaction of sodium/calcium exchanger with eNOS. Additionally intracellular alkalinization is also related to the activation of eNOS in association with Ca²⁺ influx, which is suppressed by inhibition of the Na⁺/H⁺ exchanger.

In metabolic alkalosis with compensatory hypercapnia, the subsequent constriction of the basilar artery due to lowered $P_{CO_2}$ is prolonged, is independent of cerebral spinal fluid pH over a physiological range and is independent of NO and $K_{ATP}$ channels (53).

Albuquerque and Leffler (54) reported that metabolic alkalosis ($pH_0$ 7.7, $P_{CO_2}$ 36 mmHg) in cultures of piglet cerebrovascular smooth muscle cells increased cytosolic calcium by about 80% as well as Ins(1,4,5)P3. These results were also obtained for respiratory alkalosis. Thus, cerebral vasoconstriction probably involves the production of Ins(1,4,5)P3 leading to cytosolic calcium elevation as a result of extracellular pH alteration.

**Conclusion**

NO, prostanoids and hyperpolarization may be involved in the mechanism responsible for pH-mediated vasodilatation depending on vascular bed type. What remains to be determined is if their role is predominantly permissive for the direct effect of pH change on the smooth muscle cell. Another pattern that is emerging is that the altered pHₐ can be associated with changes in pHᵢ, and the latter may be involved in the vasodilator effects.

There is much information on acid base disorders in terms of the effects on vascular reactivity but it is quite divergent. Attention must be given to differences related to species, strain, type of vessel, vessel preparation, drugs used, and pre-tension given during experimental settings.

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