Noradrenergic Tresspass in Anesthetic and Sedative States

In this issue of Anesthesiology, Hu et al. delve into the mechanisms of hypnotic action of potent volatile anesthetic agents as well as dexmedetomidine; these data build upon previous work from this and other laboratories that collectively provide insights that may affect how these agents are used in clinical practice. USING mice that lack the dopamine-β-hydroxylase (DβH) gene and are therefore incapable of synthesizing noradrenaline and adrenaline throughout the organism, the authors confirm their previous findings of enhanced sensitivity to, or delayed emergence from, volatile anesthetic agents. In addition, they corroborate that α2 adrenergic agonists (of which dexmedetomidine is the prototype in contemporary clinical practice) are capable of producing a hypnotic response, established both by behavioral and electrophysiological paradigms, in these mutated mice. Further, they show that DβH knockout mice are remarkably sensitive to dexmedetomidine, using more sophisticated electrophysiological endpoints than the previously reported loss of righting reflex. Ultimately Hu et al.’s interpretation of their data challenge the Nelson model of anesthetic action for dexmedetomidine, but not GABAergic agents, which centers on suppression of noradrenergic signaling from the locus ceruleus (fig. 1). Earlier, these investigators established that both GABAergic and noradrenergic agents activate the ventrolateral preoptic nucleus, the endogenous sleep switch; however, they proposed that dexmedetomidine appeared to do this by inhibiting noradrenergic input from the locus ceruleus into the ventrolateral preoptic nucleus while GABAergic agents act directly on ventrolateral preoptic nucleus itself.

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Mice that lack a critical gene, such as DβH (DβH−/−) mice, survive the absence of critical neurotransmitters by adaptive changes. In DβH−/− mice, there is a significant increase in the catecholamine dopamine, the substrate for the absent enzyme, which is also capable of binding to and activating both adrenergic and noradrenergic receptors, although with much lower affinity. The authors acknowledge this possibility, and devise a “reversal” experiment in which adrenergic and noradrenergic ligands are administered centrally, using a pharmacological strategy developed by one of the authors; this normalizes the sensitivity of DβH−/− mice to that seen in the wild-type control mice. However, to establish that this is solely due to replenishing the missing ligands, it would be necessary to show that this pharmacologic strategy does not nonspecifically alter sensitivity in wild-type mice that already have a full complement of catecholamines. In the absence of such data, one cannot conclude that pharmacological restoration of noradrenaline and/or adrenaline in the DβH−/− mice is the reason for normalization of the sedative response to dexmedetomidine.

Regarding the overexpression of dopamine, by binding and activating the D2 dopaminergic receptor subtype, this catecholamine is capable of decreasing the minimum alveolar concentration for halothane, whether or not a similar alteration in sensitivity obtains for α2 agonists is known. Remarkably, others have shown enhanced reversal of the hypnotic response to isoflurane with increased dopaminergic signaling. Both alternatives need to be directly addressed if one is to conclude that the enhanced sensitivity is due to the missing ligands, rather than due to the increased expression of dopamine.

Notwithstanding these issues, data provided in this article contribute to an impressive body of work from Kelz’s laboratory,

which seeks to explain communication between various brain nuclei and neurotransmitter systems for the induction and emergence from volatile and intravenous hypnotic agents.\textsuperscript{1–4} The locus ceruleus, a collection of noradrenergic neurons in the brainstem, has been considered to be pivotal for inducing the hypnotic response to dexmedetomidine based upon a series of experiments in which the agonist induced a hypnotic response when delivered discretely into that nucleus but not when administered 2 mm away.\textsuperscript{12,13} These findings were corroborated by data from experiments in which the hypnotic effects of systemically administered dexmedetomidine was blocked when an $\alpha_2$ adrenoceptor antagonist was delivered into the locus ceruleus.\textsuperscript{7} Both, because the distribution of the injectate into either site was not established, and, because of the periventricular location of this nucleus, it is conceivable that the $\alpha_2$ agonist may have initiated the hypnotic response on $\alpha_2$ adrenoceptors\textsuperscript{14} at more distant noradrenergic neurons.\textsuperscript{15} Indeed another recent study showed that knock out of the $\alpha_2$ adrenoceptor on noradrenergic neurons did not affect the hypnotic response to the $\alpha_2$ agonist medetomidine.\textsuperscript{15} Nevertheless, the critical requirement for a reduction in the firing of the locus ceruleus neurons for dexmedetomidine's hypnotic action are neither supported nor refuted by the data provided by Hsu et al. (fig. 1).\textsuperscript{1,15}

Intriguingly, and despite significant research, the role of noradrenergic signaling in natural arousal mechanisms in the brain remains unclear. Depletion of central noradrenaline or adrenaline does not affect the sleep–wake cycle, suggesting there is overlap and redundancy of neurotransmitters to control arousal states. However, noradrenergic signaling is suppressed during sleep perhaps because it plays a critical role in diverting attention to external stimuli. Suppression of this external surveillance when trying to rest may permit some of the homeostatic functions of sleep such as synaptic downscaling.\textsuperscript{16} Hence, a defining feature of sleep is that we are unaware of our environment, or disconnected.\textsuperscript{17} We have recently argued that disconnection is a critical aim of anesthesia, and hypothesized that noradrenaline plays a critical role in maintaining connectedness (the potential for an experience to be triggered by an external stimulus) during anesthesia.\textsuperscript{17} If substantiated, suppression of noradrenergic signaling would emerge as a core component of anesthesia to prevent the awareness of surgery.

Anesthetics that act on GABAergic agents type A receptors, such as propofol, pentobarbital, and the volatile anesthetics, exert little effect on noradrenergic signaling (fig. 1).\textsuperscript{5,6,8} Nevertheless, attenuation of noradrenergic signaling does increase sensitivity to GABAergic agents (as Hu et al. illustrate). Suppression of noradrenergic signaling does not appear necessary for anesthetic-induced hypnosis (defined as the patient “looking asleep”) paralleling its redundancy in the sleep–wake cycle. However, while the patient may look “asleep,” intact noradrenergic signaling may drive connectedness to the environment explaining why hypnotic doses of anesthesia always do not suppress responses on the isolated forearm technique during surgery.\textsuperscript{17} As such, noradrenergic signaling may be considered a previously unrecognized trespasser in the anesthetic state, which may promote awareness during GABAergic hypnosis.

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Fig. 1. Schematic to illustrate that the sedative/anesthetic effects of $\gamma$-aminobutyric acid–mediated (GABA) agent and $\alpha_2$ adrenergic agonists involve different subcortical neural networks. Active nuclei are depicted in red, and inactive nuclei are depicted in blue. For illustrative purposes, projections that are largely excitatory are shown as red lines; those that are largely inhibitory are shown as blue lines. (A) In the awake state, certain “awake-active” neural nuclei, including the noradrenergic locus ceruleus (LC), the orexinergic perifornical nucleus (PeF) and the histaminergic tuberomamillary nucleus (TMN), provide excitatory input to higher centers such as the corticothalamic network. Wake up, a “sleep-active” nucleus the venterolateral preoptic nucleus (VLPO) is silent. (B) During GABAergic sedation/anesthesia, potentiated inhibitory actions of the VLPO reduce neural activity in both the PeF and TMN but allow activity to proceed unimpeded in the LC (resulting in intact noradrenergic signaling to higher centers depicted by the red line). (C) During $\alpha_2$ adrenergic agonist sedation/anesthesia, activity is reduced in the LC and TMN, while activity is enhanced in the inhibitory VLPO. Activity in the PeF is unaffected by $\alpha_2$ adrenergic agonist sedation (resulting in intact orexinergic signaling to the corticothalamic network). This schematic does not convey the direct (postsynaptic) corticothalamic effects of the sedatives that also play a role in their mechanism of action. Modified with permission from intensetimes, issue 9, available at www.intensetimes.eu.\textsuperscript{24}
Delaying connectedness on emergence from hypnosis may have related consequences such as reducing postoperative and critical care delirium by preventing emergence from hypnosis at a reduced level of consciousness. This state can be considered akin to “sleep inertia” in which subjects awake confused from nonrapid eye-movement sleep; similarly, delirious patients may not have sufficient conscious cognitive processing to interact appropriately with the environment.\(^1\)\(^,\)\(^2\) Delaying connectedness by suppressing noradrenergic activity may be a way to prevent this. In turn, this may explain why dexmedetomidine decreased emergence delirium after volatile anaesthesia, agitation in pediatric patients with sleep apnea, and delirium in the mechanically ventilated patients.\(^3\)\(^–\)\(^22\) To the perioperative utility of \(\alpha\) agonists for mitigating pain, nausea, inflammation, and organ injury can now be added its putative effects on delaying connectedness. Translational studies building on the important preclinical findings by Kelz and others may edge us closer to improvements in clinical care by identifying other trespassing neurotransmitters in the anesthetic or sedated state, which can be modulated to improve perioperative and critical care outcomes.\(^23\)


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