Neurotoxicity of General Anesthetics

Cause for Concern?
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GENERAL anesthetics are highly lipid soluble and can dissolve in every membrane, penetrate into organelles, and interact with numerous cellular constituents. Their actions have long been considered rapid and fully reversible, with the pharmacodynamic time course of anesthesia dictated solely by the pharmacokinetic profiles of anesthetic uptake and elimination. But recent laboratory data call for a cautious reassessment of this assumption. In the past decade, it has become apparent that anesthetics can affect gene expression, protein synthesis and processing, and cellular function in poorly understood ways that provide plausible biochemical substrates for durable long-term effects in a number of tissues. Although in most patients physiologic homeostasis is restored soon after general anesthesia, anesthetics have potentially profound and long-lasting effects that, in animal models, seem particularly consequential in specific developmental periods and pathophysiologic contexts.

Could a class of drugs used for many decades without evidence of long-term damage have insidious and heretofore unrecognized neurotoxic effects? Here, we critically evaluate available scientific evidence for general anesthetic “neurotoxicity” and the potential clinical implications. Because the scope of this clinical commentary is limited, numerous deserving laboratory investigations could not be mentioned in this focused overview. Our goal as physician–scientists not directly involved in this area of research is to summarize the diverse directions of research in this field, while highlighting the limitations of existing data with respect to clinical practice in order to provide the reader with a rational platform for discussions with colleagues and patients. The barriers that must be overcome to permit clinical translation of the available laboratory research are emphasized, along with the need for further research, as recently highlighted in a consensus statement by a group including authoritative researchers in this field.1 As with any emerging field of research, new evidence continues to accrue such that conclusions are by necessity preliminary and will require frequent reappraisal.

Why Suspect Long-term Neurologic Effects of Anesthetics?

The degree of reversible changes induced by transient exposure to general anesthetic drugs is immense: Deep coma and suppression of nocifensive reflexes compatible with a diagnosis of brain death is followed by a rapid return to normal consciousness with discontinuation of the anesthetic. Given such profound, though reversible, alterations of central nervous system (CNS) function, some degree of long-lasting effects might well be anticipated. Anesthetic preconditioning, which minimizes ischemic damage to the heart or brain, provides a precedent for anesthetic-induced changes that outlast the physical presence of the agents. The possibility that subtle long-lasting changes might be more widespread and not necessarily beneficial in nature is therefore quite real. But caution is necessary in assessing claims of irreversible anesthetic effects. Although observations of prolonged and even irreversible cognitive changes after anesthesia have occurred over the years, it is difficult to attribute these often dramatic effects to the anesthetic drugs per se. Only studies performed using tightly controlled intraoperative and postoperative conditions can really contribute to understanding the scope and nature of the potential problem given the multiple confounding variables now recognized.

The International Study of Post-Operative Cognitive Dysfunction convincingly established the existence and prevalence of postoperative cognitive dysfunction (POCD) as a defined clinical entity in elderly patients.2 The major risk factor identified for POCD was advanced age, but mechanisms remain unknown and could involve effects of accumulating chronic disease, declining organ function, and/or altered drug responses.3 Exposure to surgery and anesthesia has also been suspected to accelerate preexisting but...
recent retrospective studies did not conclusively resolve midazolam, nitrous oxide, and isoflurane.6 Although CNS is clearly susceptible to damage induced by common anesthetic drugs, model anesthetics (alcohols and model anesthetics) for their neurodegenerative potential in neonatal animal models.5 The immature rodent CNS is clearly susceptible to damage induced by commonly used anesthetic drugs (ketamine or a cocktail of midazolam, nitrous oxide, and isoflurane).6 Although concerning, the relevance of these findings to human infants has been questioned on theoretical grounds. Recent experiments in primates provide a reassuring but preliminary new perspective7 on the rodent data. Two recent retrospective studies did not conclusively resolve the issue.8,9 For example, the incidence of learning disabilities in children with multiple anesthetic exposures before the age of 4 yr was found to be associated with a doubled incidence of learning disability diagnoses in later life.8 Despite the striking nature of this significant finding, the authors rightly pointed out that the methodologic constraints of the study preclude conclusions as to the role played by anesthesia versus surgery and other associated conditions for this long-term outcome. In the meantime, further laboratory and clinical studies are under way to clarify the clinical implications.10 Because it might take years to accurately define these risks, it is appropriate to comment on the existing laboratory data from the clinical perspective.

Extensive clinical trials have not proven or excluded a direct causal link between general anesthetics and long-term cognitive impairment.2,11,12 Given the logistical difficulties and time requirements inherent in clinical outcome studies, it is now clear that animal-based research is essential to advance our understanding and help target clinical research.1 Some of the most pressing currently unresolved questions are as follows:

1. Do anesthetic drugs per se have measurable and reproducible long-term cognitive effects in the healthy human brain, particularly at the extremes of age, and/or do cognitive deficits result from other perioperative factors, such as surgical trauma, concomitant disease, and sleep disturbance?

2. Are long-term anesthetic effects drug-specific (e.g., inhaled vs. intravenous) or the result of the (un)physiologic state of pharmacologic coma they produce?

3. What are the molecular/cellular mechanisms of neuronal toxicity, and what are the predisposing factors to injury (e.g., age/developmental stage, presymptomatic neurodegenerative disease, dementia)?

4. If clinically relevant anesthetic neurotoxicity occurs in humans (no data support this assumption thus far), is prophylaxis or treatment possible, or can new, nontoxic agents or drug combinations be developed?

The Mature and Aging Brain: A Clinical Problem in Search of Experimental Evidence?

Neurobehavioral models of learning and memory have been used to probe for long-term deficits after general anesthetic exposure of adult and aged rodents to simulate behavioral aspects of POCD. Seemingly paradoxical improvements have been observed in memory consolidation in adult rats.13 With refinement in the models, impaired learning was reported consistently within 2–3 weeks after exposure to anesthetic combinations in aged rats.14 Conversely, anesthetic exposure caused a transient improvement in cellular and behavioral measures of learning and memory on the day after exposure in adult mice15 as well as lasting improvements in memory performance of adult rats exposed to anesthetics at 2 months of age (i.e., as young adults).16 In summary, when effects on learning and memory were observed, be it improvement in adult or deterioration in aged rodents, they seemed to last for weeks, which is considerably longer than predicted by the pharmacokinetic properties of potent inhalational agents. Moreover, a 4-h exposure of aged rats to nitrous oxide alone has been reported to cause learning impairment for up to 2 weeks,17 possibly providing a behavioral correlate to the earlier finding of neuronal damage induced by nitrous oxide exposure.18 When tested in the same behavioral model, propofol did not produce delayed cognitive impairment in aged rats.19 These studies suggest that, in the absence of surgical stress, some general anesthetics have sustained effects on spatial learning and memory that outlast their physical presence in the body, whereas others do not. Confirmation of these observations (for equivalent anesthetic depths and under surgical stress) would indicate that lasting cognitive impairment is likely to be due to a drug-specific effect on the aged brain, rather than result from the anesthetic-induced comatose state per se.

The events leading to prolonged alterations of memory and their relation to in vitro biochemical changes or clinical observations are unclear, however. Current hypotheses attribute the delayed neurocognitive deficits produced by anesthetics to direct neurotoxic effects (e.g., via alteration of intracellular calcium homeostasis in the case of isoflurane20), to enhancement of endogenous neurodegenerative mechanisms, to neuroinflammatory mechanisms triggered by surgically induced systemic inflammation,21 or to age-sensitive suppression of neuronal stem cell proliferation or differentiation.16,22
Any combination of these causes or a heretofore unidentified one may also be plausible.

**Anesthetic Toxicity and Neurodegeneration**

Although the mechanism of neurodegeneration in AD is still unclear, the leading theory implicates toxic effects mediated by the accumulation and aggregation of amyloid-peptides into a variety of soluble oligomers.\textsuperscript{23–26} Amyloid β peptides of various lengths are constitutively released after proteolytic cleavage of the amyloid precursor protein (APP). Depending on various conditions, these peptides can self-assemble into toxic oligomers that correlate with the severity of cognitive impairment in AD. Insoluble deposits of Aβ that appear amorphous under light microscopy are found in abnormally high amounts in the brains of AD patients and to a lesser extent in normal age-matched humans. Although it is not entirely clear how these products of oligomerization cause neurodegeneration, considerable evidence supports the “Aβ hypothesis of AD.” Specifically, mutations of APP that increase cleavage of APP to the toxic form of Aβ (Aβ42) are associated with AD, synthetic Aβ peptides are toxic to hippocampal and cortical neurons in vitro, and injection of Aβ into the cerebral ventricles reversibly prevents induction of long-term potentiation, a cellular form of learning and memory.\textsuperscript{27} Within the framework of the Aβ hypothesis, the neurotoxic element is the intermediate-sized Aβ oligomer rather than the mature fibril. The possibility that volatile anesthetics might favor oligomerization of Aβ42 under physiologically relevant conditions is therefore intriguing.

A current hypothesis attributes a pivotal role to neurotoxic effects of Aβ42. A 2-h isoflurane anesthetic in mice activated biomarkers compatible with a transient neurotoxic effect: an increase in caspase 3 (a marker of apoptosis) 6 h after anesthesia was followed by increased Aβ 24 h after exposure.\textsuperscript{28} Whether these biochemical alterations persist beyond 24 h and/or correlate with neurobehavioral deficits was not reported. On the other hand, hyperphosphorylation of the protein τ, an important step in the genesis of neurofibrillary tangles, has been reported in vivo in mice immediately after anesthesia-induced hypothermia with various anesthetic drugs. It is noteworthy that τ hyperphosphorylation was observed in the absence of demonstrable changes in Aβ levels (at least after chloral hydrate—Aβ levels were not reported for other anesthetics).\textsuperscript{29} The preventability of these “prodegenerative” changes (by normothermia) does not directly support a simple toxicity-promoting role of general anesthetics, and demonstrates again the importance of careful control of physiologic variables, both clinically and in studies of neurotoxicity.

A causal link between anesthetic-induced changes in biochemical markers of neurotoxicity and the development long-term cognitive dysfunction assessed with a variety of behavioral tests is required to solidify the proposed link between inhaled anesthetics (the largest body of incriminating evidence implicates isoflurane) and neurodegenerative changes. If such a relation is indeed demonstrated, it will likely be dose- and context-specific. For example, Aβ is physiologically released in the healthy brain and picomolar (soluble, not oligomeric) concentrations of Aβ actually improve, whereas higher concentrations degrade long-term potentiation and memory in rodents.\textsuperscript{30,31}

**The Degeneration-prone Brain**

Are anesthetics particularly toxic to a brain in the early (presymptomatic) stages of a neurodegenerative disorder? This clinically important question has been addressed in an animal model of AD (Tg2576 transgenic mice) that harbors the human APP-Swedish mutation of APP.\textsuperscript{32} The affected hemizygous mice produce increasing amounts of Aβ and show age-dependent memory deficits by 9–10 months of age. Daily exposure of female mice to either halothane or isoflurane for 2 h over 5 consecutive days was bracketed by behavioral tests and followed by terminal immunohistochemistry 2 weeks after the anesthetic exposures. Increased cognitive impairment in the wake of anesthetic exposure was observed only in isoflurane-exposed wild-type mice, not in the baseline impaired AD mutants, whereas an increase in amyloid plaque load without worsened cognitive impairment was present in halothane-exposed AD-prone mutant mice. These results are difficult to reconcile with the hypothesis that anesthetic-induced increases in Aβ lead to cognitive impairment, but could reflect a delay in the cognitive functional effects of anesthetic-induced changes in amyloid formation. Therefore, the link between anesthetics and neurodegenerative disorders is far from conclusive, and alternative hypotheses should continue to be explored in this experimentally challenging area.

**The Role of Neuroinflammation**

The context of the anesthetic exposure might be critical to long-term neurocognitive effects. Clinical studies have not identified an effect of general versus regional anesthesia, which suggests that the surgical insult itself might play a critical role in POCD.\textsuperscript{33} Recent experiments provide evidence for a role of inflammation in early cognitive abnormalities, at least in adult animals. Neurolept anesthesia with fentanyl and droperidol together with a surgical insult (splenectomy) in rats resulted in signs of CNS inflammation and cognitive impairment on the first and third postoperative days, whereas control and anesthesia-only groups showed neither inflammatory changes nor behavioral effects.\textsuperscript{21} Immune-mediated sickness behavior is among the multiple physiologic and pharmacologic derangements occurring in the perioperative period that could impact postoperative cognitive function and must therefore be considered.
Insights from Experiments in Vitro

Experiments performed in cell-free systems and in cell or neuronal cultures cannot demonstrate neurocognitive effects but provide important mechanistic insights for correlation with laboratory studies in more intact preparations. A major effort has focused on linking anesthetic exposure to the generation of amyloid or direct neurotoxicity. Halothane and isoflurane at suprachloral concentrations accelerate oligomerization of Aβ42 and increase the amount of insoluble oligomers. In cultured pheochromocytoma cells, isoflurane and halothane were not toxic alone but augmented Aβ42-induced toxicity. These effects were specific for volatile anesthetics because propofol and ethanol at clinically relevant concentrations were ineffective. If similar processes occurred in vivo under clinically relevant conditions, volatile anesthetics could increase oligomerized Aβ42, a neurotoxic form of amyloid, in susceptible brains.

Cultured human neuroglioma (H4) cells transfected to express human APP served as a model to probe isoflurane effects on AD-related pathologic processes. A 6-h exposure to isoflurane increased apoptosis and Aβ secretion, but these effects did not seem to be linked. The primary effect of isoflurane was proposed to be increased secretion of Aβ42 leading to induction of apoptosis. Aggregation of secreted Aβ peptides, in turn, was facilitated by isoflurane and the oligomerized Aβ was proposed to promote toxicity in a cell culture model. The primary toxic effect of isoflurane could be related to intracellular Ca2+ homeostasis because isoflurane-induced apoptosis was traced to excessive release of Ca2+ from the endoplasmic reticulum via activation of inositol trisphosphate (IP3) receptors in cultured pheochromocytoma cells and chicken lymphocytes. The survival of cultured neurons was reduced by exposure to isoflurane for 24 h, but not to sevoflurane, via a mechanism linked to release of Ca2+ from intracellular stores. The relevance of these findings, especially those obtained from genetically modified and nonneuronal cells, for the brain in vivo are unknown, but warrant further studies.

The Immature Brain: Experimental Evidence in Search of Clinical Relevance

Anesthesia, Apoptosis, and Long-term Consequences

Receptors for the most abundant excitatory (L-glutamate) and/or inhibitory (γ-aminobutyric acid [GABA]) neurotransmitters are affected by all known anesthetic drugs at concentrations achieved during clinical anesthesia, but the contributions of these and other known drug–receptor interactions to their desirable or undesirable effects are far less clear. It is important to note that the signaling systems activated by these two transmitters undergo dramatic changes during the maturation of the CNS. In contrast to the mature brain, transient pharmacologic blockade of N-methyl-D-aspartate (NMDA) receptors in the developing rodent brain causes excessive neuronal apoptosis, whereas neuronal degeneration caused by ethanol is even more widespread, perhaps because of its ability to enhance GABA receptors in addition to blocking NMDA receptors.

Even though ethanol and other alkanols are used as model anesthetics in mechanistic research and the neurotoxic potential of ketamine is established, it was the demonstration that drug combinations used commonly in clinical practice produce long-lasting neurologic deficits in neonatal rats that shocked the medical community. Rat pups anesthetized on postnatal day 7 (P7) with combinations of midazolam, isoflurane, and nitrous oxide (triple cocktail) sufficient to maintain a surgical plane of anesthesia for 6 h showed excessive neuronal apoptosis in the short term, impaired electrophysiologic and behavioral measures of learning and memory as juveniles, and impaired cognitive function as adults. This publication has since achieved landmark status because of its persuasive combination of histopathology, electrophysiology, and behavioral experiments and the follow-up into adulthood of subjects exposed to the triple cocktail. Only isoflurane, when given alone, increased apoptosis in the neonate, but each additional drug (double and triple cocktails) further increased the number of apoptotic neurons (up to 15-fold). Exposure to the triple cocktail exactly at P7 caused impaired hippocampal long-term potentiation and mild deficits in spatial reference memory as adolescents (P28–32). Deficits in hippocampus-dependent learning and memory persisted into adulthood.

A number of experimental studies have confirmed the immediate neurotoxic effect of anesthetics in immature rodents and have largely excluded the possibility of confounding alterations of homeostasis (e.g., hypoglycemia, hypothermia, hypoxia). However, these studies generally did not address the important question of long-term cognitive consequences. Recent reports confirmed the early cellular-level toxicity of both isoflurane and sevoflurane when administered at P7–10, but differed significantly with respect to long-term cognitive outcomes. Behavioral deficits persisting into adulthood were found in the experiments using sevoflurane but not isoflurane. An interesting difference between these studies that both exposed the animals for 6 h to comparable concentrations of the respective inhalational agent lies in the different strains of mice used to conduct the experiments (hybrid vs. inbred). The genetically more variable crossbred mice showed no long-term impairment, indicating that the strain of mice used must be considered when interpreting experiments. In rats, by contrast, isoflurane caused both acute toxicity and delayed deficits in spatial memory, but the behavioral effect was only present after a 4-h isoflurane anesthetic and not with shorter exposures. Recent studies of injectable drugs suggest that anesthetic agents somewhat specific for NMDA or GABA receptors (ketamine, thiopental, and propofol, either alone or in combination) when adminis-
Fig. 1. Developmental vulnerability to neurotoxicity due to paradoxical γ-aminobutyric acid (GABA)-mediated excitation. Animal models have provided convincing evidence for drug-induced apoptotic neurodegeneration. The peaks of vulnerability to early (E19) and late (P7) apoptotic neurodegeneration induced by ethanol in rat brain are indicated. The development of rat brain compared with that of the macaque is shown in the lower axes, with approximate corresponding developmental milestones. Neurogenesis occurs before E80 in primates, which corresponds to birth in rats. A single day in rat neurodevelopment (P7) translates to 32 days in primates. Note that axons develop before dendrites and spines, and GABA synapses before glutamate synapses. Excitotoxicity resulting from GABA, enhancing anesthetics is considered a plausible model for neurodegeneration. During development, GABA changes from excitatory (depolarizing) to inhibitory (hyperpolarizing) because the intracellular chloride concentration decreases as a result of changes in the expression of the two major chloride cotransporters, KCC2 and NKCC1, which are differentially expressed during development. Paradoxical excitation of immature neurons by activation of GABA receptors generates an efflux of chloride and excitation in immature neurons (left inset), in contrast to the influx of chloride with inhibition in mature neurons (right inset).

tered to P10 mice can also cause behavioral deficits or alterations in adulthood. However, it should be noted that the specificity of, for example, ketamine for NMDA receptors may be less than previously thought, and hence attributing any outcomes to specific drug–receptor interactions could be premature. Overall, this evidence, suggesting that anesthetics with different molecular mechanisms of action can potentially increase apoptosis in the rodent brain and lead to long-lasting neurobehavioral consequences, is compatible with the notion that prolonged pharmacologic coma might be detrimental irrespective of the causative condition.

Mechanisms of Neurotoxicity

A consistent requirement for anesthetic neurotoxicity is that exposure to anesthetic drugs must be substantial in terms of both duration and dose as well as precisely timed to coincide with the brain growth spurt, a period of intense neurogenesis and synaptogenesis. Many more neurons and synapses are formed throughout development than survive into adulthood to form the 10^11 neurons and 10^14 synapses in the adult human brain. Programmed cell death (apoptosis) and synaptic pruning are critical to plasticity and stabilization of circuits in the developing nervous system. These are active processes that are tightly controlled by neurotrophin signaling mechanisms to ensure normal development, facilitate synaptic plasticity, and prevent neoplasia. It is commonly assumed that apoptosis is induced by an unphysiologic “blackout” during this critical period, which, if long enough, causes synaptic connections to degenerate and thus “disconnected” neurons to undergo apoptosis. The mechanistic details have yet to be established. An excitotoxic effect of GABA-mediated anesthetic drugs acting to potentiate excitatory GABA receptors during early development is a prime candidate (fig. 1). Blockade of NMDA receptors has been suggested to produce excitotoxicity due to compensatory increases in NMDA receptor expression after sustained blockade. After withdrawal of the blocker, increased Ca2+ influx could lead to both apoptotic and necrotic cell death. Evidence also suggests that isoflurane can affect the balance between the forms of the neurotrophin brain-derived neurotrophic factor that promote neuron survival or death and neuronal spine stability or retraction. What other pathways for toxicity exist and whether there are overlaps with neurotoxicity in the aged brain remain to be clarified.

Stem Cells/Apoptosis?

Anesthetic-induced apoptosis of neural stem cells is a possible mediator of neurotoxicity that could explain effects at both extremes of age. Recent evidence indicates that functionally important neurogenesis continues at a low level in specific brain regions throughout life, particularly in the dentate gyrus of the hippocampus, where its selective blockade causes delayed memory deficits in adult animals. Neural precursor cells obtained from P2 rat pups and grown in culture did not undergo apoptosis or necrosis after exposure to 4 h of 3.7% isoflurane but were slowed in their proliferation and showed accelerated neuronal differentiation. Exposure to 4 h of 1 minimum alveolar concentration isoflurane also decreased progenitor proliferation in P7 but not young adult rats. Whether and how
these changes relate to long-term cognitive deficits remains
to be determined, but it seems that these changes may be
more relevant for the immature than the mature brain.

Clinical Relevance
The relevance of these findings to clinical anesthesia in
pediatric patients has naturally generated a vigorous and
ongoing debate resulting from a conflict between concern-
ning preclinical laboratory findings and established clinical
practices. Although available retrospective clinical trials are
not incompatible with the existence of associations be-
tween early anesthetic exposure and long-term neurocogni-
tive function, the aforementioned limitations indicate
that time-consuming randomized prospective trials are re-
quired. Two principal arguments have been raised by
skeptics of the clinical relevance of anesthetic neurotoxic-
ity. The first is that neuronal damage and its sequelae (in
rodent models without surgical intervention) are due to
causes other than the anesthetic drugs, an argument that
has been largely refuted. The second argument is based on
the profound differences between mammalian species in
neurodevelopmental time course and hence timing and
relative duration of exposure in potentially anesthetic-sen-
sitive critical periods. Related to timing is also the extrap-
olation of the duration of exposure necessary to inflict
damage.

The neonatal rodent is the flagship animal model for
studies of neonatal anesthetic toxicity. Rats and mice, how-
ever, are altricial, whereas other species, e.g., guinea pigs,
primates, and ungulates, are precocial. The brain growth
spurt occurs later in the former, predominantly prenatally
or both prenatally and postnatally in the latter. Accordingly,
histopathologic evidence of toxicity in guinea pigs was
documented after exposure to anesthetics in utero, but its
reproducibility postnatally as well as behavioral relevance
are unknown. The important question is therefore when the
developing primate brain is vulnerable and what consti-
tutes a critical threshold (dose × time) of anesthetic
exposure. Only a partial answer is available and only for
ketamine: Exposure of rhesus monkey fetuses and new-
borns to ketamine for 24 h caused neurodegeneration at
day 122 of gestation (75–80% of normal term, roughly
comparable to P7 in rat and nominally to 20–28 weeks of
gestation in humans, but see the milestone-based calcula-
tion below) and on P5, but not on P35. Conversely, a 3-h
exposure at P5 had no neurodegenerative effect. Although
ketamine has the most consistently reproducible, dose-
dependent effects in rodent models and these data might
seem reassuring, the animal numbers examined were small
and behavioral consequences were not assessed. Studies to
detect subtle changes and whether other anesthetics fol-
low a similar profile are necessary. Despite these caveats,
the data obtained from rhesus monkeys are consistent with
contemporary comparative neurobiologic data using a de-
velopmental milestones–based approach by which the
brain of a P7 rat pup corresponds to the brain of a human
embryo of 16–22 weeks of gestation, and are also compat-
ible with previously published estimates for the peak
vulnerability of human fetuses to excitotoxic damage. An
additional, purely quantitative factor that could complicate
interspecies extrapolation is the varying fraction of neurons
that normally undergo apoptosis during gestation. In the
human cerebral cortex, the number of neurons peaks at
28–32 weeks of gestation and is reduced by 70% by the
early postnatal period. If this fraction is substantially differ-
ent from rodents, the long-term impact of additional, drug-
induced apoptosis on cognitive function might also differ.
Differences between rodent and primate brain with re-
spect to developmental flexibility, compensatory mecha-
nisms, and susceptibility to exogenous modulators could
also be involved.

Conclusions
In light of the existing evidence reviewed in this article,
the question is not so much whether long-lasting anesthet-
ic-induced changes in the CNS can occur, but whether they
have any identifiable or preventable deleterious impact in
the long term when used clinically. Convincing evidence to
that effect is lacking but is probably unattainable because of
methodologic constraints of studies in human subjects.
Nevertheless, both retrospective and prospective outcome
studies are under way in an effort to define the impact of
general anesthetics on long-term cognitive func-
tion. In the meantime, more evidence is required from
animal models that more closely mimic the clinical reality.
Considering that there are no alternatives to the available
anesthetic drugs in most cases (to the best of our knowl-
edge, long-term consequences of silencing the developing
spinal cord have not been studied, and acute local anes-
thetic neurotoxicity is beyond the scope of this review), it
becomes incumbent on anesthesiologists and intensivists
to use existing drugs judiciously while developing ways to
minimize potential for harm. Given the major gaps in our
understanding of the neurocognitive consequences of an-
esthetic exposure with and without surgical stress and the
paucity of convincing clinical evidence implicating or ac-
quitting anesthetic drugs per se, it is appropriate to remem-
ber that no drugs are free of side effects but also to reassure
our patients about their general safety. Cause for concern?
Yes. Cause for continued research efforts? Definitely. Cause
to adjust sound clinical practice? No. Stay tuned.

References
1. Baranov D, Bickler PE, Crosby GJ, Calley DJ, Eckenhoff MF, Eckenhoff RG,
Hogan KJ, Jevtovic-Todorovic V, Palotas A, Perooansky M, Planell E, Silverstein JH,
Wei H, Whittington RA, Xie Z, Zuo Z. Consensus statement: First International
Rabbi P, Jolles J, Larsen K, Hanning CD, Lauven PM, Planel E, Silverstein JH, Langer
