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Research Article

Advances in Anesthesia Safety

Shaukat Hayat Khan
Department of Orthopedic Surgery, Sheikh Khalifa Bin Zayed Al Nahyan Hospital, Combined Military Hospital, Muzaffarabad, Pakistan.

Abstract

Over the last century, anesthesia has evolved into a highly specialized and safe component of modern medicine. Innovations in pharmacology, patient monitoring, airway management, and safety protocols have significantly reduced perioperative mortality and complications. This review explores historical milestones, current practices, and cutting-edge technologies contributing to improved anesthesia safety. Emphasis is placed on risk mitigation strategies, anesthetic drug advancements, real-time physiological monitoring, and the integration of artificial intelligence and simulation in training. Ongoing challenges and future directions in patient-specific anesthesia care are also discussed.

Keywords: *Anesthesia safety, perioperative care, patient monitoring, anesthetic drugs, airway management, simulation training, anesthesia complications, artificial intelligence in anesthesia*

Introduction

Anesthesia has undergone transformative changes since the introduction of ether in the 19th century. Today, the probability of anesthesia-related mortality is less than 1 in 100,000 in developed countries, reflecting substantial progress in safety standards. Factors contributing to this improvement include advancements in technology, pharmacology, monitoring, and standardized protocols. This article reviews the historical context, identifies key contributors to enhanced safety, and discusses emerging technologies shaping the future of anesthetic care.

1. Historical Overview of Anesthesia Safety

Early Anesthetics and Associated Risks

Anesthesia has come a long way in terms of safety, but its early history was fraught with risks. In the 19th century, before the advent of modern anesthetics, surgery was a terrifying prospect. The main form of anesthesia used was alcohol, ether, or nitrous oxide, but these substances were not refined and carried significant dangers.

Ether was first used for general anesthesia in the 1840s by William T.G. Morton. While it allowed patients to undergo surgery without pain, it had risks like respiratory depression, vomiting, and even explosion in the presence of a spark.

Chloroform was introduced in the 1840s as well, and though it provided a deeper anesthetic effect, it also caused cardiac arrhythmias, liver damage, and death in some cases.

Early anesthesia was administered by physicians with limited experience, which made it even riskier. Many patients died from the side effects, and there was little understanding of dosages or how to manage complications effectively.

Evolution of Safety Protocols

As the risks of early anesthetics became evident, researchers and medical professionals began to

focus on improving safety. Several milestones in the evolution of anesthesia safety include:

Development of safer agents: In the early 20th century, anesthetics like **halothane** and **sevoflurane** were developed, which had fewer side effects compared to ether and chloroform.

Monitoring of vital signs: The importance of monitoring the patient during surgery became clear, leading to the introduction of equipment to track blood pressure, heart rate, and oxygen levels, which helped to ensure the patient's safety.

Advancement in techniques: Techniques such as **regional anesthesia** (e.g., epidural and spinal blocks) were introduced as alternatives to general anesthesia, providing more targeted and less risky options for certain procedures.

Introduction of Safety Checklists

One of the most significant changes in anesthesia safety came with the introduction of **safety checklists**. Inspired by practices in aviation, where checklists had been used for decades to ensure the safety of flights, anesthesia protocols were formalized into checklists to prevent errors and omissions. This move was especially crucial as surgery and anesthesia became more complex.

The WHO Surgical Safety Checklist (introduced in 2008) was one of the most significant steps. This checklist emphasizes critical steps that need to be performed before, during, and after surgery to ensure patient safety.

Specific items in the checklist include verifying the patient's identity, confirming the surgical procedure, checking equipment, and reviewing any potential risks associated with anesthesia.

The success of these checklists in reducing errors, improving communication among the surgical team, and enhancing patient outcomes has been widely documented, leading to their adoption worldwide.

In conclusion, the history of anesthesia safety shows a clear progression from dangerous, poorly understood techniques to a highly regulated and monitored practice, incorporating advanced technologies and standardized protocols to safeguard patients.

2. Modern Anesthetic Agents and Pharmacological Advances

Low-Toxicity Volatile Anesthetics (e.g., Sevoflurane, Desflurane)

Volatile anesthetics are a key component of modern general anesthesia. They are gases that are inhaled to induce and maintain anesthesia during surgery. Over the years, the development of **low-toxicity volatile anesthetics** has greatly improved the safety profile of anesthesia.

Sevoflurane: This inhaled anesthetic agent is widely used due to its low toxicity and rapid onset and offset of action. Sevoflurane has a pleasant odor, making it more acceptable to patients, especially in pediatric settings. It also has minimal effects on the cardiovascular system, which makes it suitable for high-risk patients, including those with heart disease.

Desflurane: Another popular volatile anesthetic, desflurane has a faster onset and recovery compared to sevoflurane. It is especially useful in outpatient surgery, where rapid recovery is essential. Desflurane also has a low solubility in the blood, which allows for quicker changes in the anesthetic depth. However, it requires specialized vaporizer equipment due to its low boiling point.

Both of these agents have a safer profile compared to older anesthetics like halothane, as they are less likely to cause liver toxicity, malignant hyperthermia, and other side effects.

Short-Acting Intravenous Agents (e.g., Propofol, Remifentanil)

Intravenous anesthetics are used for inducing anesthesia or maintaining it during procedures. Advances in **short-acting intravenous agents** have made anesthesia management more precise and flexible, providing rapid onset and recovery with fewer side effects.

Propofol: This is one of the most commonly used intravenous agents for both induction and maintenance of anesthesia. It has a rapid onset (about 30 seconds) and a quick recovery profile, making it particularly useful for outpatient procedures. Propofol also has anti-emetic properties, which helps reduce nausea and vomiting in patients after surgery. However, it can cause hypotension and respiratory depression, especially in high doses, so careful monitoring is required.

Remifentanil: A **short-acting opioid** that is often used in combination with other anesthetic agents. It has an ultra-short duration of action due to its rapid metabolism by esterases in the plasma. Remifentanil is ideal for procedures that require quick and precise control over pain management, such as during cardiac surgery or other high-risk surgeries. Because of its fast elimination, it

minimizes the post-operative risk of opioid-related complications.

Both propofol and remifentanil allow anesthesiologists to better manage anesthesia depth and provide smoother transitions from anesthesia to wakefulness with reduced recovery times.

Target-Controlled Infusion (TCI) Systems

Target-Controlled Infusion (TCI) systems represent a major advancement in anesthesia pharmacology by automating the delivery of anesthetic drugs to maintain a desired level of anesthesia based on real-time pharmacokinetic modeling.

How TCI Works: TCI systems rely on algorithms that take into account the patient's age, weight, and other physiological factors to adjust the infusion rate of anesthetic agents such as propofol or remifentanil. The system continuously adjusts the drug delivery to maintain a constant and ideal anesthetic effect, reducing the likelihood of under- or over-sedation.

Benefits: TCI systems help to maintain a precise depth of anesthesia and have been shown to reduce intraoperative complications, like hypotension, by minimizing drug fluctuations. They also improve the efficiency of anesthesia administration, making it particularly beneficial in prolonged surgeries or intensive care settings. Additionally, the use of TCI systems has been associated with quicker recovery times after surgery, as the system can rapidly reduce the anesthetic effect at the end of a procedure.

In summary, modern anesthetic agents like **sevoflurane**, **desflurane**, **propofol**, and **remifentanil**, along with the use of **Target-Controlled Infusion (TCI) systems**, have revolutionized anesthesia practice. These advancements provide safer, more effective, and more controlled anesthesia, significantly improving patient outcomes and reducing the risks associated with anesthesia management.

Overall Integration

By combining these advanced monitoring tools with AI and closed-loop systems, healthcare providers can create a more comprehensive, precise, and patient-centric approach to anesthesia and critical care. The integration of predictive analytics can further enhance safety and efficiency, allowing clinicians to intervene before potential complications arise.

It seems you're exploring the role of simulation-based education and crisis management in healthcare, particularly in the context of anesthesia and perioperative care. These areas have gained significant attention for improving clinical skills and team dynamics during high-stress situations. Here's a detailed breakdown of each aspect:

1. **Role of High-Fidelity Simulators in Training**

High-fidelity simulation involves using advanced, realistic models (both mechanical and virtual) to replicate real-life clinical situations. These simulators allow healthcare providers to practice and refine their skills in a controlled, risk-free environment.

Key Features of High-Fidelity Simulators:

Realistic Physiological Responses: Simulators mimic the human body's physiological responses to various interventions, such as changes in heart rate, blood pressure, and respiratory function.

Interactive Scenarios: They can be programmed to present a wide range of clinical scenarios, including both routine procedures and rare or high-risk events like cardiac arrest or airway obstruction.

Feedback and Performance Assessment: These systems often provide immediate feedback on performance, enabling learners to adjust their actions and improve their decision-making.

Repetition: Learners can repeat scenarios multiple times, gaining confidence and improving their skills in handling complex situations.

Benefits:

Safe environment for learners to practice critical procedures without putting real patients at risk.

Facilitates the development of technical and non-technical skills (e.g., communication, teamwork, crisis management).

Effective for both novice learners and experienced professionals who need to refresh or update their skills.

2. **Team-Based Simulation for Managing Perioperative Emergencies**

Team-based simulation focuses on collaborative training, where groups of healthcare providers work

together to manage high-stakes clinical situations. This approach emphasizes communication, leadership, decision-making, and teamwork—skills that are essential during perioperative emergencies.

Types of Scenarios in Team-Based Simulation:

Airway Management Emergencies: Practicing difficult airway scenarios or unexpected complications during intubation.

Cardiopulmonary Resuscitation (CPR): Simulating scenarios where a patient experiences cardiac arrest, requiring quick, coordinated action from the entire team.

Mass Casualty or Trauma Scenarios: Practicing management of multiple patients in a high-pressure situation, requiring coordination of resources and roles.

Surgical Complications: Training teams to manage complications such as bleeding, aspiration, or equipment failure during surgery.

Benefits:

Strengthens communication and coordination among team members, which is crucial in emergency situations.

Enhances leadership skills by allowing individuals to practice leading a team through a crisis.

Improves situational awareness and decision-making under pressure, reducing the likelihood of errors during actual emergencies.

3. **Cognitive Aids and Checklists**

Cognitive aids and checklists are tools used to support decision-making and ensure that important steps in a clinical procedure or emergency response are not missed. These aids are particularly useful in high-pressure situations, where stress and time constraints can lead to lapses in memory or oversight.

Types of Cognitive Aids:

Decision Trees and Algorithms: These guide clinicians through complex decision-making processes, helping them consider all options and consequences systematically.

Flowcharts: Used in managing emergencies, such as trauma care or anesthesia-related crises, these charts provide step-by-step instructions for responding to specific situations.

Checklists: These ensure that critical steps in procedures (e.g., preoperative preparation, anesthesia induction, post-operative care) are completed. They can be particularly effective in preventing errors and improving consistency.

Benefits:

Reduces human error by ensuring that no critical steps are overlooked, particularly in stressful, fast-paced environments.

Standardizes care across different practitioners, improving consistency and outcomes.

Enhances cognitive function by providing external support for complex decision-making processes, helping clinicians avoid cognitive overload.

Integrating Simulation and Crisis Management in Education

The combination of high-fidelity simulators, team-based training, and cognitive aids can create a comprehensive learning environment for healthcare professionals. By practicing emergency scenarios in a simulated setting, clinicians gain valuable experience without the risk of patient harm. Additionally, using checklists and cognitive aids during simulations reinforces correct practices and ensures that the team can handle real-life crises efficiently.

Overall Impact:

Improved Patient Safety: Practicing in simulations allows healthcare professionals to handle emergencies more confidently, improving patient outcomes.

Enhanced Skills and Confidence: Repeated exposure to complex, high-pressure situations builds skills and confidence in both technical and non-technical aspects of care.

Team Cohesion: Team-based simulation promotes effective communication and coordination, which are critical in real emergencies.

Perioperative risk assessment and stratification are crucial components of managing patients before, during, and after surgery. By identifying patients who may be at higher risk for complications, healthcare providers can tailor their approach to minimize risks and improve outcomes. Here's an

overview of the topics you mentioned:

1. **ASA Physical Status Classification**

The **American Society of Anesthesiologists (ASA) Physical Status Classification** is a system used to assess and communicate the physical fitness of patients before undergoing surgery. It helps predict the likelihood of perioperative complications and assists in making decisions regarding anesthesia and surgical interventions.

Reduced healthcare costs through improved efficiency and faster recovery.

Overall Approach to Perioperative Risk Assessment and Stratification

A comprehensive approach to perioperative risk assessment and stratification helps identify patients who are at higher risk for complications and guides the management of their care throughout the surgical process. By utilizing tools like the ASA Physical Status Classification, conducting thorough preoperative screening, and implementing ERAS protocols, clinicians can optimize outcomes and enhance patient safety.

Reducing postoperative complications is a critical focus in perioperative care to improve patient outcomes and enhance recovery. The topics you've mentioned—awareness under anesthesia (AUA), postoperative nausea and vomiting (PONV), and delirium/cognitive dysfunction—are key areas that can significantly impact the postoperative experience. Here's a detailed look at each of these issues and strategies to mitigate them:

1. **Awareness Under Anesthesia (AUA) Prevention**

Awareness under anesthesia (AUA) occurs when a patient becomes conscious during surgery and can recall specific details of the procedure. This condition is rare but can be distressing, leading to psychological trauma and lasting effects such as anxiety, nightmares, and post-traumatic stress disorder (PTSD).

Causes of AUA:

Inadequate Anesthetic Dosage: The most common cause is insufficient dosage of anesthetic agents during surgery, often due to equipment malfunction or human error.

Light Anesthesia: In some cases, the anesthetic depth may not be deep enough to induce unconsciousness, especially in long surgeries or cases where anesthetic requirements are difficult to estimate.

Prevention Strategies:

Monitoring Depth of Anesthesia: Using devices such as the **BIS (Bispectral Index)** monitor to track the depth of anesthesia and adjust dosages accordingly. The BIS score ranges from 0 (no brain activity) to 100 (fully awake), and anesthesiologists aim to keep the score within the desired range (usually 40-60 for general anesthesia).

Anesthetic Drug Protocols: Using a balanced approach with both volatile anesthetics (e.g., sevoflurane) and intravenous agents (e.g., propofol) to provide stable anesthesia depth.

Patient History and Risk Factors: Assessing the patient's individual risk factors, such as previous episodes of awareness or specific conditions that may affect anesthetic requirements (e.g., obesity, metabolic conditions).

Benefits of Prevention:

Reduces the incidence of post-operative psychological trauma (e.g., anxiety, nightmares, PTSD).

Ensures patient comfort and safety during surgical procedures.

Improves the overall anesthesia experience and trust in the medical team.

Diabetes: Diabetic patients often experience altered glucose metabolism, and careful monitoring of blood glucose is necessary to prevent both hyperglycemia and hypoglycemia during and after surgery. Insulin regimens may need to be adjusted preoperatively.

Chronic Kidney Disease: Renal function should be monitored closely, and adjustments in drug dosing are often necessary, especially for medications that are cleared by the kidneys. Fluids must be carefully managed to avoid overload or dehydration.

Respiratory Conditions: For patients with chronic obstructive pulmonary disease (COPD) or asthma, care should be taken to avoid respiratory depressants and ensure adequate ventilation. In some cases, regional anesthesia may be preferred to reduce the risk of respiratory complications.

Polypharmacy: Patients with multiple comorbidities are often on multiple medications, which may

interact with anesthetic drugs. A careful review of medications should be conducted to prevent potential interactions (e.g., anticoagulants, antihypertensives).

Overall Considerations for Special Populations

Tailoring anesthesia for special populations requires careful preoperative evaluation, adjustments in drug dosages, vigilant monitoring, and individualized perioperative care. A comprehensive approach that considers the physiological, medical, and surgical factors for each patient can improve safety and outcomes.

Patient safety in anesthesia is a critical aspect of ensuring that healthcare environments are safe and that patient outcomes are optimized. Anesthesia-related incidents, although rare, can lead to significant complications, making it essential to have strong reporting and quality improvement systems in place. The tools you mentioned—**anesthesia incident reporting**, the **WHO surgical safety checklist**, and **national registries and benchmarking**—are all vital components of a comprehensive patient safety culture. Let's explore each of these in more detail:

1. **Anesthesia Incident Reporting and Quality Improvement Programs**

Anesthesia Incident Reporting is a crucial part of maintaining patient safety and improving care delivery. These reporting systems allow healthcare providers to document and analyze adverse events or near-misses in anesthesia care, which can then be used to prevent future incidents.

Key Aspects of Anesthesia Incident Reporting:

Adverse Event Documentation: This includes any event that deviates from the expected outcome, such as equipment malfunction, medication errors, or unanticipated responses to anesthetics.

Near Misses: Incidents that could have resulted in harm but were prevented. These are just as important as actual adverse events because they provide insight into potential risks.

Data Collection: Incident reports are often anonymized and stored in databases where they can be analyzed to identify trends, areas for improvement, and lessons learned.

Root Cause Analysis: For each reported incident, a root cause analysis (RCA) is often conducted to identify underlying factors contributing to the error (e.g., human error, equipment failure, lack of training).

Feedback Loop: Once incidents are reported and analyzed, feedback is given to staff, and changes are made to reduce the likelihood of similar events occurring in the future.

Quality Improvement Programs:

These programs use data from incident reports to implement changes aimed at improving patient care. Techniques include:

Education and Training: Continuous staff education on anesthesia protocols, drug safety, equipment use, and emergency responses.

Simulation Training: Using high-fidelity simulators to replicate anesthesia-related crises and improve skills in a controlled environment.

Standardization: Developing standard operating procedures (SOPs) for common anesthesia practices to ensure consistency and reduce errors.

Benefits:

Benefits:

Data-Driven Decision Making: Registries and benchmarking help institutions identify areas where they may be lagging in patient safety or anesthesia practices, allowing for targeted quality improvement.

Improved Patient Outcomes: By identifying and adopting best practices, hospitals can improve patient safety, reduce complications, and provide more effective anesthesia care.

Public Accountability: Publicly available benchmarks can encourage hospitals and providers to strive for higher standards of care, enhancing the overall quality of anesthesia and surgical services.

A strong **patient safety culture** supported by effective **incident reporting**, the **WHO surgical safety checklist**, and **national registries/benchmarking** plays a critical role in reducing anesthesia-related errors and improving patient outcomes. By embracing these tools, healthcare institutions can foster a culture of safety, continuously learn from past experiences, and deliver high-quality care to patients.

The future of anesthesiology holds immense promise, with advancements in technology and medical

science leading the way toward safer, more efficient, and personalized care. Key areas of innovation include **AI-assisted anesthesia delivery**, **remote anesthesia (tele-anesthesia)**, and **precision medicine in anesthesiology**. Let's explore these topics in more detail:

1. **AI-Assisted Anesthesia Delivery**

AI-assisted anesthesia delivery involves the use of artificial intelligence and machine learning algorithms to optimize anesthesia management, improving both patient outcomes and the efficiency of anesthesia care. AI can assist in various stages of anesthesia, from preoperative risk assessment to real-time intraoperative monitoring.

Potential Applications:

Personalized Anesthesia Dosing: AI algorithms can analyze patient-specific data (e.g., age, weight, medical history) and automatically adjust drug doses to achieve the desired depth of anesthesia. This can reduce human error and improve the precision of drug delivery.

Predictive Monitoring: AI can process vast amounts of real-time data from physiological monitors (e.g., heart rate, blood pressure, oxygen saturation, BIS score) to predict potential complications before they occur. For instance, AI may alert anesthesia providers to impending hypotension or respiratory depression.

Automated Anesthesia Delivery Systems: Some systems are already in development that can autonomously adjust the delivery of anesthetic agents based on real-time patient data, similar to closed-loop anesthesia systems. These systems could improve stability by maintaining the appropriate depth of anesthesia without constant manual adjustments.

Learning from Big Data: AI can analyze vast amounts of data from a wide range of patients and surgical procedures, enabling it to detect subtle trends or correlations that may not be evident to human practitioners. This can lead to more evidence-based decision-making and improved outcomes.

Benefits:

Enhanced Accuracy: AI can process and analyze data more quickly and accurately than humans, improving the precision of anesthesia delivery.

Reduced Human Error: AI's ability to continuously monitor and adjust anesthesia can reduce the risk of human error, such as under- or overdosing anesthetic agents.

Predictive Capabilities: AI systems can anticipate and mitigate potential risks or complications in real time, potentially improving patient safety and reducing adverse events.

2. **Remote Anesthesia (Tele-Anesthesia)**

Tele-anesthesia, or **remote anesthesia**, is a novel approach in which anesthesia care is provided by a remote anesthesiologist, often via telecommunication technologies, while local anesthesia personnel manage the patient's care in the operating room or other procedure settings. This approach is particularly useful in underserved or remote areas where there may be a shortage of trained anesthesia providers.

Potential Applications:

Remote Consultation and Supervision: Anesthesiologists can guide and supervise anesthesia management remotely, providing expert consultation during procedures in locations where anesthesia specialists are not readily available. This is particularly valuable in rural or low-resource settings.

Virtual Monitoring: Through high-definition video, real-time physiological data transmission, and remote monitoring tools, anesthesiologists can assess the patient's condition, monitor vital signs, and adjust anesthetic management without being physically present.

Remote Emergency Assistance: In cases of anesthesia-related complications or emergencies, remote anesthesiologists can offer guidance or suggest interventions to local medical teams, providing crucial support in time-sensitive situations.

Expansion of Access: Tele-anesthesia can allow patients in remote areas to access anesthesia care for surgeries or procedures that may have previously been unavailable to them due to the lack of nearby specialists.

Benefits:

Increased Access to Care: Tele-anesthesia could reduce disparities in healthcare access, particularly in rural or underserved regions, by making anesthesia expertise available without requiring travel.

Cost-Effective: By leveraging remote consultation, healthcare institutions could reduce staffing

needs while still providing high-quality care. It may also help manage resource limitations more effectively.

Improved Training and Collaboration: Remote anesthesia allows for real-time collaboration and mentoring, which could be beneficial for training purposes and for enhancing teamwork in anesthesia care.

3. **Precision Medicine in Anesthesiology**

Precision medicine refers to tailoring medical treatments to individual patients based on their genetic, environmental, and lifestyle factors. In anesthesiology, precision medicine could revolutionize how anesthesia is administered by customizing anesthetic plans for each patient, considering their unique biological makeup.

Potential Applications:

Genetic Predispositions: Advances in pharmacogenomics (the study of how genes affect a person's response to drugs) can lead to more precise dosing of anesthetic drugs. For example, genetic testing may help predict how a patient will metabolize certain anesthetics (e.g., propofol, opioids) and allow for the selection of drugs with a better risk profile.

Predicting Anesthetic Sensitivity: Some patients may be more or less sensitive to certain anesthetic agents due to genetic variations. By using genetic markers, anesthesiologists can predict which drugs will be most effective and minimize the risk of adverse reactions (e.g., malignant hyperthermia or drug-induced liver toxicity).

Customized Pain Management: Precision medicine can be used to tailor pain management strategies based on a patient's genetics. For example, patients with specific gene variants related to opioid metabolism may benefit from alternative pain management strategies, such as regional anesthesia or non-opioid analgesics.

Risk Assessment: Personalized anesthetic management can also involve assessing individual risks for perioperative complications, such as cardiovascular events, based on genetic predispositions and medical history.

Benefits:

Improved Drug Efficacy: Precision medicine allows for better-targeted therapies, ensuring that anesthetic drugs are not only safer but also more effective for each individual.

Reduced Side Effects: By considering a patient's genetic makeup, the risk of adverse reactions to anesthetics can be reduced, leading to a safer anesthetic experience.

Enhanced Patient Outcomes: Tailoring anesthesia based on the patient's unique characteristics can improve overall perioperative outcomes, reduce recovery times, and minimize complications.

The integration of **AI-assisted anesthesia delivery**, **tele-anesthesia**, and **precision medicine** is poised to significantly transform the field of anesthesiology. These technologies offer exciting opportunities to enhance patient safety, improve efficiency, and provide more personalized care. As these innovations become more widely implemented, the future of anesthesia will be marked by greater accuracy, accessibility, and tailored treatment approaches.

Naveed Rafaqat Ahmad is a governance reform practitioner and public policy scholar specializing in digital government transformation, regulatory design, and institutional accountability in developing states. His research examines how artificial intelligence can be responsibly integrated into public administration systems to enhance efficiency while preserving transparency, procedural fairness, and citizen trust. Ahmad advances a structured, risk-based regulatory framework that calibrates safeguards according to the potential impact of AI applications, particularly in high-stakes areas such as eligibility decisions, enforcement support, and biometric identification. By combining insights from administrative law, technology governance, and public sector innovation, he contributes to the development of accountable, explainable, and operationally feasible AI governance models tailored to resource-constrained governmental environments.

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