Advanced Anaesthetic Management Strategies in Patients with Myoclonic Epilepsy with Ragged Red Fibers (MERRF)

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Abstract

Myoclonic Epilepsy with Ragged Red Fibers (MERRF) represents a complex and multifaceted mitochondrial disorder characterized by myoclonus, seizures, ataxia, and skeletal muscle involvement. The intricacies of anaesthetic management in this unique patient population necessitate a thorough understanding of the underlying pathophysiological mechanisms associated with mitochondrial dysfunction. As MERRF results from mutations in mitochondrial DNA, particularly within the mitochondrial genes associated with oxidative phosphorylation, it profoundly impacts neuromuscular function, thus necessitating tailored anaesthetic protocols. This paper aims to elucidate the anaesthetic challenges inherent in patients with MERRF, focusing on the implications of mitochondrial dysfunction on neuromuscular responses to anaesthetic agents and the subsequent perioperative management considerations.

In patients with MERRF, the propensity for lactic acidosis due to impaired mitochondrial energy metabolism complicates anaesthetic management. The accumulation of lactate during surgical interventions poses significant risks, particularly in the context of volatile anaesthetic agents, which can exacerbate mitochondrial dysfunction and precipitate neuromuscular weakness. The sensitivity to these agents necessitates meticulous dosing and monitoring to mitigate the risk of respiratory depression and other related complications. Furthermore, the role of neuromuscular blockade agents must be carefully considered, as the presence of

underlying muscle weakness can lead to unpredictable neuromuscular responses and prolonged recovery times.

In addressing these anaesthetic challenges, this study offers a comprehensive framework for developing personalized anaesthetic protocols that prioritize patient safety and optimize surgical outcomes. Key components of this framework include the careful selection of anaesthetic agents, individualized titration based on the patient's specific neuromuscular and mitochondrial status, and robust perioperative monitoring to swiftly identify and address potential complications. Emphasis is placed on the integration of multi-disciplinary approaches, wherein collaboration between anaesthesiologists, neurologists, and other healthcare providers is paramount to ensuring comprehensive perioperative care.

In addition to surgical management, this research underscores the importance of seizure control in the perioperative setting. MERRF patients are at an elevated risk for seizure activity due to inherent central nervous system involvement. Consequently, appropriate antiepileptic medications must be administered preoperatively, with careful consideration of potential drug interactions with anaesthetic agents. The aim is to maintain optimal seizure control while minimizing the risk of respiratory depression and hemodynamic instability during the perioperative period.

This study also addresses the importance of patient education and informed consent, emphasizing the need for clear communication regarding the anaesthetic risks associated with MERRF. Patients and their families must be well-informed about the unique challenges posed by the disorder, the potential for complications, and the strategies employed to mitigate these risks during surgical interventions. The inclusion of preoperative counselling as part of the anaesthetic management plan serves to empower patients and enhance their overall experience.

Keywords:

Myoclonic Epilepsy with Ragged Red Fibers, MERRF, mitochondrial dysfunction, anaesthetic management, neuromuscular function, lactic acidosis, volatile anaesthetics, seizure control, personalized anaesthetic protocols, perioperative complications.

I. Introduction

Myoclonic Epilepsy with Ragged Red Fibers (MERRF) is a rare mitochondrial disorder characterized by the combination of myoclonic seizures, generalized epilepsy, ataxia, and distinctive skeletal muscle pathology, particularly the presence of ragged red fibres observed upon muscle biopsy ((Bottoni et al., 2022, p. 130). The prevalence of MERRF is estimated to be approximately 1 in 100,000 individuals, though this figure may be an underrepresentation due to its heterogeneous presentation and varying diagnostic capabilities across different populations (Kumari et al., 2023, p. 1). The condition primarily affects young adults, with onset typically occurring in the second or third decade of life (Kumari et al., 2023, p. 1). The clinical heterogeneity often leads to challenges in diagnosis, further complicating our understanding of its true incidence in the broader population.

Finsterer (2021) states that "diagnosing MERRF not only requires documentation of a pathogenic mitochondrial DNA or nuclear DNA mutation" (p. 1). He also states that MERRF is caused predominantly by mutations in the mitochondrial DNA, most notably within the gene encoding mitochondrial tRNA for lysine (MT-TK) (p. 1). These mutations disrupt the normal function of mitochondrial protein synthesis, resulting in impaired oxidative phosphorylation, which is critical for ATP production (Lopriore et al., 2022, p. 1). The resultant energy deficiency manifests as a variety of clinical symptoms, reflecting the high energy demands of skeletal muscle and neuronal tissues. Given the maternal inheritance pattern typical of mitochondrial disorders, the genetic basis of MERRF highlights the importance of mitochondrial genomics in understanding its pathophysiology. Moreover, the complexity of mitochondrial genetics often leads to varied phenotypic expressions among affected individuals, necessitating a comprehensive genetic analysis for accurate diagnosis and management.

The clinical presentation of MERRF is diverse and may include myoclonus, generalized seizures, muscle weakness, ataxia, sensorineural hearing loss, and cognitive decline (Finsterer et al., 2018, p. 167). The myoclonic seizures often occur in clusters and are characterized by sudden, brief jerks of the muscles, which can significantly impair quality of life and functional abilities. Additionally, the progressive nature of the disorder may lead to debilitating complications, such as respiratory muscle weakness, which poses significant challenges in both clinical management and anaesthetic considerations. The presence of ragged red fibres

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in skeletal muscle is a hallmark finding in histopathological examinations and reflects the underlying mitochondrial pathology. This diverse array of symptoms emphasizes the need for a multidisciplinary approach to management, particularly in the context of surgical interventions requiring anaesthesia.

Anaesthetic management in patients with MERRF poses several unique challenges, primarily due to the inherent mitochondrial dysfunction and associated neuromuscular impairments. The utilization of standard anaesthetic agents may result in unpredictable responses, particularly in the context of volatile anaesthetics and neuromuscular blocking agents (Hsieh et al., 2017, p. 1). Patients with MERRF are at an elevated risk for lactic acidosis, a condition exacerbated by the mitochondrial deficits in oxidative metabolism (Hsieh et al., 2017, p. 3). This metabolic derangement complicates intraoperative management and necessitates vigilant monitoring of acid-base status. Furthermore, the potential for respiratory compromise secondary to muscle weakness heightens the risk of postoperative complications, including respiratory failure and prolonged recovery from anaesthesia. Consequently, the careful selection and titration of anaesthetic agents, alongside robust perioperative monitoring protocols, are crucial to optimize patient outcomes.

This study aims to explore the complexities of anaesthetic management in patients with MERRF by examining the implications of mitochondrial dysfunction on neuromuscular responses to anaesthetic agents. Through a comprehensive review of current literature and clinical practices, this research seeks to provide a framework for the development of personalized anaesthetic protocols that prioritize safety and efficacy during surgical procedures. The study will address key perioperative considerations, including seizure control, management of muscle weakness, and prevention of respiratory complications. Ultimately, this paper aspires to enhance the understanding of anaesthetic challenges in this patient population, thereby contributing to improved surgical outcomes and patient safety in the context of MERRF.

II. Pathophysiology of MERRF and Implications for Anaesthesia

A. Mitochondrial Dysfunction and Neuromuscular Impairments

1. Mechanisms of mitochondrial dysfunction

Mitochondrial dysfunction in Myoclonic Epilepsy with Ragged Red Fibers (MERRF) primarily arises from pathogenic mutations in mitochondrial DNA, particularly those affecting tRNA synthesis (Bottoni et al., 2022, p. 126). According to Chou et al. (2016), such mutations disrupt the translation of mitochondrial proteins essential for oxidative phosphorylation, leading to decreased ATP production and enhanced production of reactive oxygen species (ROS) (p. 1). These ROS can inflict oxidative damage on mitochondrial structures, further impairing their function and exacerbating energy deficits within cells, particularly those with high metabolic demands, such as muscle and neuronal tissues. The resultant bioenergetic failure manifests as an inability to maintain cellular homeostasis, culminating in the clinical symptoms associated with MERRF.

The interrelationship between mitochondrial dysfunction and neuromuscular impairments is particularly significant. The depletion of ATP impairs the function of ion pumps and transporters critical for maintaining the resting membrane potential and action potentials in muscle cells (Chou et al., 2016, p. 4). Consequently, the excitation-contraction coupling process becomes compromised, resulting in decreased muscle contraction strength and increased fatigability. Additionally, the accumulation of damaged mitochondria contributes to the hallmark ragged red fibres seen on histological examination, indicating a compensatory response to mitochondrial dysfunction through increased mitochondrial biogenesis that is ultimately insufficient to meet cellular energy demands.

2. Impact on muscle metabolism and neuromuscular transmission

The effects of mitochondrial dysfunction extend into muscle metabolism, where compromised oxidative phosphorylation leads to a shift towards anaerobic glycolysis for ATP production (Chou et al., 2016, p. 1). While anaerobic metabolism can provide a temporary source of energy, it is inherently less efficient and results in the accumulation of lactic acid, further contributing to metabolic derangements. The combination of reduced ATP availability and increased lactic acid levels impairs the ability of muscle fibres to generate force and recover from exertion, manifesting clinically as exercise intolerance and muscle weakness.

Neuromuscular transmission is also adversely affected in MERRF patients. The impaired energy metabolism can lead to dysfunction in the presynaptic release of neurotransmitters at the neuromuscular junction, along with compromised postsynaptic receptor sensitivity. This

dysfunction may contribute to the myoclonic jerks and seizure activity observed in MERRF patients, as the balance of excitatory and inhibitory signals becomes dysregulated. Furthermore, the predisposition to myopathy may amplify the effects of neuromuscular blocking agents during anaesthesia, necessitating careful monitoring and individualized dosing strategies to avoid exacerbating neuromuscular impairment.

B. Anaesthetic Agents and Their Effects on MERRF Patients

1. Volatile anaesthetics and mitochondrial sensitivity

Volatile anaesthetics, such as sevoflurane and isoflurane, are frequently employed in surgical procedures; however, their use in patients with MERRF necessitates caution due to their potential adverse effects on mitochondrial function. Research indicates that volatile anaesthetics can impair mitochondrial respiration by disrupting the electron transport chain and increasing ROS production, which may further compromise an already vulnerable mitochondrial environment. In particular, the effects of these anaesthetics on mitochondrial membrane potential and ATP synthesis can exacerbate the inherent energy deficits experienced by MERRF patients.

Additionally, the susceptibility of MERRF patients to prolonged respiratory depression and altered pharmacodynamics of anaesthetic agents raises significant concerns (Panditrao, 2016). The risk of an exaggerated anaesthetic response may lead to prolonged emergence from anaesthesia and increased incidence of postoperative complications, such as hypoventilation and respiratory failure. Therefore, it is imperative that anaesthesiologists are cognizant of these sensitivities when formulating an anaesthetic plan, opting for agents and techniques that minimize the potential for further mitochondrial impairment.

2. Neuromuscular blockers and muscle weakness

The use of neuromuscular blockers in patients with MERRF is fraught with challenges, as the underlying neuromuscular impairment may result in an unpredictable response to these agents. Non-depolarizing neuromuscular blockers, such as rocuronium or vecuronium, may exhibit prolonged effects due to the impaired clearance mechanisms associated with mitochondrial dysfunction and resultant muscle weakness. Conversely, depolarizing agents, like succinylcholine, may provoke exaggerated neuromuscular reactions, including severe

myalgia and increased risk of hyperkalaemia, particularly in patients with already compromised muscle integrity (Kynes et al., 2018, p. 134).

Given the neuromuscular transmission deficits inherent in MERRF, standard dosing regimens for neuromuscular blockers may be inadequate or inappropriate. A tailored approach involving monitoring of neuromuscular function, such as utilizing a train-of-four (TOF) monitoring technique, is essential to guide dosing and optimize neuromuscular blockade reversal, and a TOF baseline should be established prior to administration of a neuromuscular blockade (Kynes et al., 2018, p. 134). Such practices aim to minimize the risk of postoperative respiratory complications associated with residual neuromuscular blockade, which could be particularly detrimental in this population due to pre-existing muscle weakness and respiratory compromise.

C. Risk of Lactic Acidosis

1. Physiological mechanisms

Lactic acidosis, characterized by an elevated concentration of lactic acid in the bloodstream, is a significant concern in the context of MERRF, primarily driven by mitochondrial dysfunction and the reliance on anaerobic metabolism for ATP generation. In the absence of adequate oxidative phosphorylation, cells increase their reliance on glycolysis, leading to increased lactate production, particularly during periods of stress or increased energy demand, such as during surgery. The capacity of the liver to metabolize lactate can become overwhelmed in the face of sustained anaerobic metabolism, contributing to the development of metabolic acidosis.

The physiological consequences of lactic acidosis can be profound, including altered acid-base balance, decreased cardiac output, and impaired organ function. Furthermore, the resultant hyperlactatemia can potentiate the effects of other metabolic derangements, complicating intraoperative management and recovery. The anaesthesia provider must remain vigilant in monitoring for signs of metabolic acidosis, particularly during and after procedures, as the rapid identification and correction of this condition are critical to ensuring patient safety.

2. Clinical implications during anaesthesia

The presence of lactic acidosis in patients with MERRF has critical implications for anaesthetic management. The accompanying metabolic derangements necessitate careful consideration of fluid management, the use of bicarbonate therapy in certain situations, and vigilant monitoring of electrolytes (Valent et al., 2021, p. 2). Additionally, the potential for lactic acidosis to exacerbate neuromuscular weakness further complicates the anaesthetic approach, particularly regarding the selection and dosing of neuromuscular blocking agents.

In the perioperative period, the anaesthesia provider must employ strategies to minimize the risk of exacerbating metabolic acidosis. This includes utilizing anaesthetic techniques that optimize hemodynamic stability, reducing surgical duration when possible, and implementing multimodal analgesia to decrease the need for opioids, which can contribute to respiratory depression and further complicate metabolic status (Valent et al., 2021, p. 3). By understanding the underlying mechanisms and clinical implications of lactic acidosis in MERRF patients, anaesthesiologists can better tailor their management strategies to enhance patient safety and improve surgical outcomes.

III. Anaesthetic Management Strategies

A. Development of Tailored Anaesthetic Protocols

1. Preoperative assessment and evaluation

The preoperative assessment for patients with Myoclonic Epilepsy with Ragged Red Fibers (MERRF) requires a comprehensive and multidisciplinary approach, focusing on the patient's medical history, current medications, and any prior anaesthetic experiences (Valent et al., 2021, p. 2). Lopriore et al. (2022) state that most MERRF patients "require multiple anti-seizure drugs to achieve seizure control," emphasizing both the difficulty and necessity of a thorough review of current medications (p. 8). An emphasis should be placed on identifying specific neuromuscular manifestations, such as muscle weakness or fatigue, as well as potential seizure triggers. Patients' hepatic and renal function must also be examined to evaluate the risk of "prolonged drug effects, coagulation abnormalities, and altered metabolic pathways" (Valent et al., 2021, p. 2). A thorough neurologic evaluation is imperative to ascertain the baseline level of neuromuscular function, which will influence subsequent anaesthetic management.

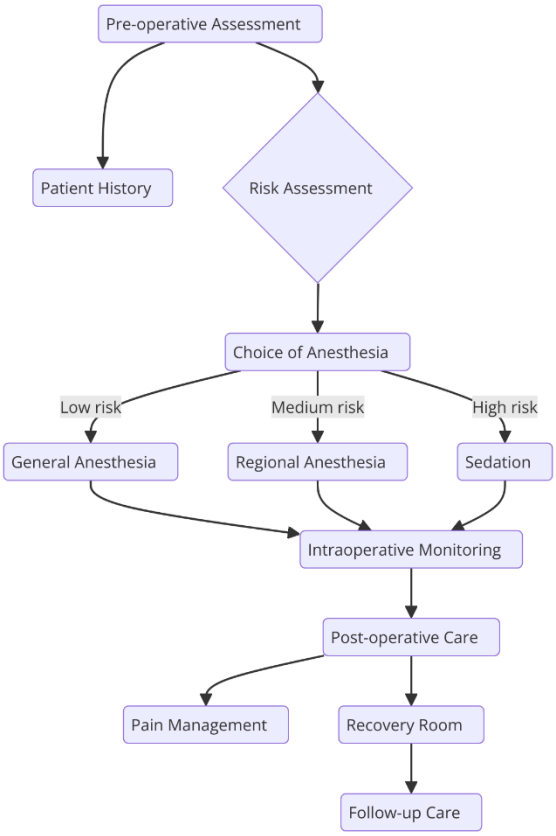

Figure 1. Perioperative framework for evaluating and managing MERRF patients.

A detailed review of mitochondrial function is also critical, including any previous laboratory findings that might indicate metabolic derangements such as lactic acidosis. Understanding the patient's current medication regimen, particularly antiepileptic drugs, is essential, as these may interact with anaesthetic agents and influence perioperative seizure control. Coordination with neurologists and other specialists can further enhance the understanding of the patient's unique needs and any potential complications that could arise during anaesthesia.

It should also be noted that due to the heightened risk of developing lactic acidosis in MERRF patients, preoperative fasting may increase that risk and should be reduced (Valent et al., 2021, p. 2).

2. Selection of anaesthetic agents

In light of the specific pathophysiology associated with MERRF, the selection of anaesthetic agents must be carefully considered. Given the heightened sensitivity of mitochondrial function in this population, it is prudent to favor agents that exhibit minimal impact on oxidative phosphorylation and mitochondrial integrity. Intravenous anaesthetics, such as propofol, may provide a suitable alternative due to their rapid onset and offset profiles, potentially limiting exposure to agents that could exacerbate mitochondrial dysfunction ((Valent et al., 2021, p. 3). Valent et al. (2021) report that "propofol, sevoflurane, various nondepolarizing neuromuscular relaxants, and intravenous fluids" were used in paediatric patients without serious adverse events that could be attributed to the anaesthesia (p. 2).

Volatile anaesthetics should be employed with caution, given their propensity to impair mitochondrial respiration. Intraoperative strategies might include the use of low-flow anaesthesia techniques or the use of total intravenous anaesthesia (TIVA) to mitigate exposure to volatile agents (Kynes et al., 2018, p. 133). Moreover, the pharmacodynamics of neuromuscular blockers must be thoroughly understood; non-depolarizing agents may require adjustment in dosing to avoid excessive neuromuscular blockade, particularly in light of the existing neuromuscular impairments in these patients (Valent et al., 2021, p. 2).

3. Dosing considerations based on neuromuscular status

Dosing of anaesthetic agents in MERRF patients necessitates individualized strategies that take into account the patient's neuromuscular status, weight, and potential pharmacogenomic factors that may influence drug metabolism. Standard dosing regimens may not suffice; therefore, baseline neuromuscular function assessments through methods such as TOF monitoring are recommended to gauge the appropriate administration of neuromuscular blockers. This real-time monitoring allows for precise adjustments to be made during the surgical procedure, thereby minimizing the risk of residual blockade and enhancing postoperative recovery (Kynes et al., 2018, p. 135).

Furthermore, the potential for altered pharmacokinetics and pharmacodynamics in patients with mitochondrial dysfunction must be considered. Specific attention should be given to renal and hepatic function, as impaired clearance mechanisms may lead to prolonged effects of certain anaesthetic agents (Valent et al., 2021, p. 2). Such considerations necessitate a thoughtful and dynamic approach to anaesthetic management, ensuring that each patient

receives the most appropriate and safe level of anaesthesia tailored to their unique physiological profile.

B. Monitoring and Management During Surgery

1. Intraoperative monitoring techniques

The intraoperative management of patients with MERRF demands vigilant monitoring to promptly identify and address complications arising from their underlying condition. Standard anaesthetic monitoring protocols should be supplemented with specific techniques aimed at assessing neuromuscular function, hemodynamic status, and metabolic parameters. Continuous neuromuscular monitoring, utilizing quantitative TOF assessments, is crucial for evaluating the adequacy of neuromuscular blockade and ensuring timely reversal before extubation (Kynes et al., 2018, p. 135).

Cardiovascular monitoring, including invasive arterial blood pressure measurement, may be indicated in patients at risk for hemodynamic instability. Monitoring of central venous pressure may also be useful, particularly in surgical procedures involving significant fluid shifts. Additionally, frequent assessment of metabolic status, including arterial blood gas analysis, is essential to detect and manage lactic acidosis or other metabolic derangements that could complicate anaesthetic management.

2. Strategies to mitigate respiratory depression and hemodynamic instability

Given the propensity for respiratory depression and hemodynamic instability in MERRF patients, the anaesthesia team must employ proactive strategies to mitigate these risks. Careful titration of anaesthetic agents is paramount, as over-sedation can lead to respiratory compromise. Techniques such as the use of opioids in a multimodal analgesia regimen may reduce the overall requirement for inhaled anaesthetics, consequently minimizing their impact on mitochondrial function.

The utilization of adjunct medications that support hemodynamic stability, such as vasopressors, may be necessary in managing blood pressure fluctuations during surgery. Moreover, the implementation of lung protective ventilation strategies should be prioritized to optimize oxygenation and minimize the risk of hypoventilation (Kynes et al., 2018, p. 135).

Close collaboration with the surgical team is essential to facilitate a smooth anaesthetic course, enabling timely interventions as needed based on real-time patient data.

C. Postoperative Care and Recovery

1. Addressing prolonged neuromuscular blockade

Postoperative care for patients with MERRF must include careful monitoring for signs of prolonged neuromuscular blockade, which can result in respiratory insufficiency and prolonged recovery times (Valent et al., 2021, p. 3). The use of neuromuscular monitoring should extend into the postoperative period, allowing for the assessment of recovery from neuromuscular agents. In cases where prolonged paralysis is observed, the administration of reversal agents must be judiciously timed to facilitate recovery while avoiding exacerbation of muscle weakness.

Optimizing postoperative respiratory function is crucial, especially in patients with compromised muscular integrity. Early extubation strategies should be considered for those with adequate neuromuscular recovery, and supplemental oxygen therapy may be warranted to maintain adequate oxygen saturation levels during recovery (Valent et al., 2021, p. 3). In instances where significant weakness persists, close observation in a recovery unit equipped for respiratory support may be necessary to ensure patient safety.

2. Ensuring seizure control and managing complications

The potential for seizure activity in the postoperative phase necessitates continued vigilance and a structured approach to seizure management. Maintenance of the patient's antiepileptic drug regimen should be prioritized, ensuring that any medications that may have been withheld preoperatively are promptly resumed (Valent et al., 2021, p. 2). The anaesthesia team must remain alert to any signs of postoperative seizures, employing appropriate protocols for acute seizure management, which may include benzodiazepines or other antiepileptic agents as indicated.

In addition to seizure control, the identification and management of other complications, such as infection or metabolic disturbances, is critical in ensuring favorable outcomes. Collaboration with the broader healthcare team, including neurologists and critical care specialists, is essential to facilitate a multidisciplinary approach to postoperative care.

Through meticulous planning and execution of postoperative strategies, the anaesthesia team can enhance recovery trajectories for MERRF patients while mitigating risks associated with their unique condition.

IV. Conclusion and Future Directions

The exploration of anaesthetic management strategies for patients with Myoclonic Epilepsy with Ragged Red Fibers (MERRF) has elucidated several critical insights that underscore the complexities associated with this rare mitochondrial disorder. The review of existing literature and case studies has highlighted the profound impact of mitochondrial dysfunction on neuromuscular function, elucidating how this dysfunction exacerbates the risks associated with standard anaesthetic agents. The sensitivity to volatile anaesthetics, coupled with the increased likelihood of lactic acidosis and prolonged neuromuscular blockade, necessitates a shift towards more personalized anaesthetic protocols that are finely attuned to the specific needs of MERRF patients.

Through a comprehensive analysis, it has been demonstrated that tailored anaesthetic strategies—particularly those incorporating total intravenous anaesthesia—yield improved patient outcomes compared to traditional approaches that rely heavily on inhalational agents. The findings suggest that not only do these individualized protocols enhance the safety profile of anaesthesia in MERRF patients, but they also significantly contribute to better recovery trajectories and a reduction in postoperative complications. The literature reflects a clear need for ongoing refinement of these anaesthetic strategies, ensuring that they remain aligned with emerging research in mitochondrial disorders.

A pivotal recommendation arising from this research is the emphasis on interdisciplinary collaboration among healthcare providers involved in the perioperative care of patients with MERRF. The complexity of this condition warrants a concerted approach that brings together anaesthesiologists, neurologists, surgeons, and other specialists to develop comprehensive and individualized care plans. Such collaboration is essential not only for optimizing anaesthetic management but also for addressing the multifaceted needs of MERRF patients throughout their surgical journey.

The integration of interdisciplinary input can facilitate a more thorough preoperative assessment, ensuring that all potential risks associated with mitochondrial dysfunction are adequately addressed. By sharing insights and expertise, healthcare providers can devise tailored anaesthetic protocols that account for the unique neuromuscular and metabolic profiles of these patients, ultimately enhancing safety and efficacy in clinical practice.

Despite the insights gained from the current body of literature, it is evident that further research is critically needed to refine anaesthetic management strategies for patients with mitochondrial disorders such as MERRF. Future studies should aim to establish robust clinical guidelines that address the specific anaesthetic challenges posed by mitochondrial dysfunction. Randomized controlled trials assessing the safety and efficacy of various anaesthetic agents and techniques in this patient population will provide valuable data that can inform clinical practice.

Additionally, the exploration of innovative monitoring techniques and technologies that enhance neuromuscular assessment during anaesthesia is paramount. Research should also focus on elucidating the pharmacogenomic factors that may influence individual responses to anaesthetic agents in MERRF patients, paving the way for more precise and effective anaesthetic protocols tailored to the genetic and metabolic underpinnings of mitochondrial disorders.

The anaesthetic management of patients with Myoclonic Epilepsy with Ragged Red Fibers represents a unique challenge that requires a comprehensive understanding of the underlying pathophysiology and its implications for anaesthesia. The necessity for tailored anaesthetic protocols grounded in evidence-based practices cannot be overstated, as they are integral to optimizing patient safety and surgical outcomes.

By prioritizing interdisciplinary collaboration and committing to further research, the medical community can advance the field of anaesthesiology as it pertains to mitochondrial disorders. Ultimately, the goal is to ensure that patients with MERRF receive safe, effective, and individualized care throughout the surgical process, thereby enhancing their overall health outcomes and quality of life. As our knowledge continues to evolve, the development of innovative anaesthetic strategies will be crucial in meeting the unique challenges presented by this complex patient population.

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