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Forensic Applications of Magnetic Resonance Spectroscopy and Near-Infrared Spectroscopy in Traumatic Brain Injury: Metabolic and Hemodynamic Perspectives in Invisible Cerebral Damage

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ABSTRACT

Traumatic brain injury (TBI) remains one of the leading causes of neurological disability worldwide and represents a major challenge in forensic medicine, particularly in cases involving persistent symptoms without visible structural abnormalities on conventional neuroimaging. This study analyzed the forensic and clinical relevance of magnetic resonance spectroscopy (^1H-MRS) and near-infrared spectroscopy (NIRS) in the evaluation of traumatic brain injury, emphasizing their role in detecting metabolic, neuronal, and hemodynamic alterations associated with invisible cerebral damage. A qualitative and integrative analytical methodology based on contemporary scientific literature was employed to examine the diagnostic contribution of advanced spectroscopic techniques compared with conventional imaging modalities. The findings demonstrated that spectroscopic methods identified a higher frequency of abnormalities than traditional structural imaging, particularly reductions in N-acetylaspartate, altered metabolic

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ratios, elevated choline concentrations, lactate peaks, and cerebral oxygenation disturbances. These alterations were associated with persistent neurological manifestations including cognitive impairment, chronic headache, emotional instability, and sleep disturbances. From a forensic perspective, spectroscopy demonstrated significant relevance in causality assessment, injury severity classification, disability evaluation, and support of medico-legal expert reports. The results support the concept that traumatic brain injury should be interpreted as a multidimensional neurometabolic disorder rather than solely as a structural lesion. Although advanced spectroscopic techniques present technical and interpretative limitations, their integration into multidisciplinary forensic evaluation may strengthen diagnostic precision and improve the objective documentation of post-traumatic cerebral dysfunction.

KEYWORDS

Traumatic brain injury, magnetic resonance spectroscopy, near-infrared spectroscopy, forensic medicine, diffuse axonal injury, cerebral metabolism, neuroimaging, cerebral oxygenation, invisible brain injury, neurometabolic dysfunction

INTRODUCTION

Traumatic brain injury (TBI) remains one of the leading causes of mortality, long-term neurological disability, and forensic controversy worldwide, particularly among young adults and economically active populations. Despite advances in neurocritical care and neuroimaging, the precise characterization of diffuse neuronal injury and metabolic dysfunction continues to represent a major diagnostic challenge in both clinical and medico-legal settings. Conventional neuroimaging modalities such as computed tomography (CT) and standard magnetic resonance imaging (MRI) are highly effective for identifying macroscopic structural abnormalities; however, they frequently fail to detect subtle axonal damage, metabolic impairment, and microvascular alterations associated with mild or moderate TBI, especially during early stages or in patients presenting persistent neurological symptoms without visible structural lesions [1], [4], [6].

In recent years, advanced spectroscopic techniques have emerged as promising tools for improving the detection and characterization of traumatic cerebral injury. Among these, proton magnetic resonance spectroscopy (^1H-MRS) and near-infrared spectroscopy (NIRS) have attracted increasing scientific and forensic interest due to their ability to identify biochemical and hemodynamic alterations that are not visible through conventional imaging approaches. These technologies provide objective evidence of neuronal dysfunction, cerebral hypoxia, altered metabolism, and diffuse axonal injury, thereby offering additional diagnostic precision in cases where structural imaging findings may appear normal [5], [8], [18].

The relevance of this topic extends beyond the clinical management of TBI. From a forensic perspective, the inability to objectively demonstrate brain injury in patients with persistent neurocognitive symptoms often generates significant legal and ethical challenges, particularly in cases involving traffic accidents, occupational trauma, assault, or medico-legal compensation disputes. In many situations, conventional radiological findings may underestimate the true extent of neurological damage, complicating the establishment of causality, injury severity, and long-term disability. Consequently, the incorporation of advanced metabolic and optical neuroimaging techniques into forensic medicine could significantly improve the objectivity and reliability of expert evaluations [3], [9], [14].

Magnetic resonance spectroscopy allows non-invasive quantification of cerebral metabolites associated with neuronal integrity, membrane turnover, and energetic metabolism. Metabolites such as N-acetylaspartate (NAA), choline (Cho), creatine (Cr), lactate, and glutamate/glutamine complexes provide valuable information regarding neuronal loss, gliosis, demyelination, mitochondrial dysfunction, and excitotoxicity after traumatic injury. Reduced NAA levels have consistently been associated with axonal disruption and poor neurological outcomes, whereas elevated choline

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concentrations may reflect membrane degradation and inflammatory activity [7], [18]. Additionally, the presence of lactate peaks has been correlated with anaerobic metabolism, cerebral ischemia, and severe secondary injury processes [9].

Simultaneously, near-infrared spectroscopy has gained relevance as a non-invasive bedside technology capable of continuously monitoring cerebral oxygenation and hemodynamic status. NIRS operates through the differential absorption of near-infrared light by oxyhemoglobin and deoxyhemoglobin, enabling real-time assessment of cerebral oxygen saturation and regional perfusion dynamics. This technique has demonstrated utility in detecting intracranial hematomas, cerebral hypoxia, impaired autoregulation, and secondary ischemic insults following TBI [3], [8], [12]. Furthermore, its portability and relative accessibility make NIRS particularly attractive in emergency, prehospital, and resource-limited settings where access to advanced neuroimaging may be restricted [17], [19].

Recent investigations have demonstrated that metabolic and hemodynamic biomarkers derived from spectroscopy correlate with neurological prognosis, cognitive impairment, neuropsychological deficits, and long-term functional outcomes after TBI [2], [10], [14]. Advances in neuroimaging research have also emphasized the growing role of multimodal monitoring strategies integrating spectroscopy, cerebral oxygenation measurements, intracranial pressure monitoring, and biomarker analysis to improve diagnostic accuracy and individualized patient management [4], [11], [20]. These findings support the growing consensus that traumatic brain injury should not be interpreted solely as a structural lesion but rather as a complex neurometabolic disorder involving dynamic biochemical, vascular, inflammatory, and neurophysiological alterations [6], [9].

Despite the increasing international evidence supporting the utility of spectroscopy in TBI, significant disparities remain regarding its implementation in forensic and clinical practice, particularly in Latin American countries. Limited technological infrastructure, reduced access to advanced neuroimaging equipment, economic constraints, and insufficient specialist training continue to restrict the incorporation of these modalities into routine medico-legal protocols. Consequently, there is a need for updated academic analyses exploring the diagnostic, prognostic, and forensic implications of spectroscopic techniques within the context of traumatic brain injury assessment [1], [5], [17].

The present study aims to analyze the forensic utility and clinical impact of magnetic resonance spectroscopy and near-infrared spectroscopy in traumatic brain injury, emphasizing their role in detecting invisible neuronal damage, improving diagnostic precision, and strengthening medico-legal evaluations. The investigation is based on the hypothesis that advanced spectroscopic techniques provide objective metabolic and hemodynamic evidence capable of complementing conventional neuroimaging findings and enhancing the assessment of traumatic cerebral injury in complex forensic scenarios.

Methodologically, the study adopts an analytical and integrative review approach focused on recent scientific evidence concerning spectroscopic applications in TBI. The design of the investigation aligns with the proposed hypothesis by examining the biochemical, physiological, and forensic contributions of ^1H-MRS and NIRS, as well as their correlation with neurological outcomes and legal implications. Through the integration of current literature, neuroimaging findings, and forensic considerations, this article seeks to contribute to the development of more objective and multidisciplinary strategies for the evaluation of traumatic brain injury in contemporary forensic medicine.

DEVELOPMENT

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Traumatic brain injury represents a complex clinical and forensic condition in which the visible structural lesion does not always reflect the real biological magnitude of cerebral damage. In many patients, especially those with mild or moderate traumatic brain injury, conventional computed tomography or standard magnetic resonance imaging may appear normal despite the presence of persistent cognitive, behavioral, emotional, or neurological manifestations. This diagnostic gap is highly relevant in forensic medicine because the absence of visible radiological injury can weaken the objective demonstration of trauma, complicate the establishment of causality, and generate uncertainty in legal evaluations related to disability, occupational injury, traffic accidents, assault, or long-term neuropsychological sequelae [1], [4], [6].

The central problem is that traumatic brain injury is not only a mechanical event but also a dynamic neurometabolic process. After the initial impact, the brain undergoes a cascade of secondary alterations that include ionic imbalance, mitochondrial dysfunction, excitotoxicity, oxidative stress, neuroinflammation, impaired cerebral autoregulation, hypoxia, ischemia, and diffuse axonal injury. These mechanisms may progress even when the initial structural imaging does not show evident hemorrhage, fracture, edema, or focal lesion. For this reason, the forensic evaluation of traumatic brain injury requires tools capable of identifying functional and metabolic abnormalities, not only anatomical changes [6], [9], [11].

In this context, magnetic resonance spectroscopy and near-infrared spectroscopy provide a complementary perspective. While conventional imaging answers the question of whether a visible lesion exists, spectroscopy helps answer a deeper question: whether the brain tissue shows biochemical or hemodynamic evidence of injury. This distinction is essential because many post-traumatic manifestations are related to alterations in neuronal metabolism, axonal integrity, oxygen delivery, and cellular energy failure rather than to macroscopic lesions alone [5], [8], [18].

Proton magnetic resonance spectroscopy has particular value because it allows the non-invasive assessment of cerebral metabolites. N-acetylaspartate is considered a marker of neuronal and axonal integrity; therefore, its reduction after trauma suggests neuronal dysfunction, axonal compromise, or loss of viable neural tissue. Choline, in contrast, is associated with membrane turnover and may increase in the presence of demyelination, gliosis, inflammation, or cellular membrane disruption. Creatine is frequently used as a reference metabolite because it reflects cerebral energy metabolism, although it may also vary under pathological conditions. Lactate elevation indicates anaerobic metabolism and may suggest hypoxia, ischemia, or mitochondrial impairment. Glutamate and glutamine alterations are also relevant because they reflect excitotoxic mechanisms involved in secondary brain injury [7], [18].

From a forensic perspective, these metabolic findings are important because they can provide objective support in cases where the clinical symptoms are disproportionate to conventional imaging results. A patient may present memory impairment, irritability, sleep disturbance, executive dysfunction, headache, emotional instability, or reduced occupational performance after head trauma, while CT or conventional MRI remains normal. In such situations, metabolic abnormalities detected through magnetic resonance spectroscopy may help demonstrate that the symptoms are biologically plausible and related to post-traumatic cerebral dysfunction [2], [10], [14].

Near-infrared spectroscopy contributes from a different but complementary angle. Its main strength lies in its capacity to assess cerebral oxygenation and hemodynamic behavior in a non-invasive and continuous manner. By measuring the absorption of near-infrared light by oxyhemoglobin and deoxyhemoglobin, NIRS allows estimation of regional cerebral oxygen saturation. This is especially useful in acute trauma, emergency care, prehospital settings, intensive care units, and environments where access to advanced imaging may be delayed or limited [5], [8], [12].

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The forensic relevance of NIRS is linked to its ability to document physiological compromise in real time. Cerebral hypoxia, impaired perfusion, hematoma-related asymmetry, and secondary ischemic insults are not merely clinical events; they may influence prognosis, disability, and medicolegal interpretation. In traumatic brain injury, secondary injury can be as important as the initial impact, and documenting these processes may help reconstruct the evolution of the lesion, estimate severity, and support expert conclusions regarding preventability, timing, and clinical consequences [3], [8], [12].

Another important point is that spectroscopy strengthens the concept of traumatic brain injury as a continuum rather than a binary condition. Traditional forensic evaluation often depends on the presence or absence of visible lesions; however, modern neuroscience shows that traumatic injury may exist along a spectrum of structural, metabolic, functional, and neuropsychological alterations. A normal CT scan does not exclude cellular injury, just as a mild clinical presentation does not necessarily exclude persistent cerebral dysfunction. Spectroscopic technologies help reduce this uncertainty by adding measurable biological data to the evaluation [6], [14], [18].

The relationship between spectroscopy and prognosis is also relevant. Several studies have reported associations between metabolic alterations, cerebral oxygenation abnormalities, cognitive impairment, and functional outcomes after traumatic brain injury. Reduced NAA, altered NAA/Cr ratios, increased choline, lactate presence, and impaired regional oxygenation may correlate with greater injury severity, worse recovery, or persistent neurological deficits [7], [10], [18]. Although spectroscopy should not be interpreted in isolation, its findings may contribute to a more complete prognostic assessment when integrated with clinical examination, neuropsychological testing, conventional imaging, and other biomarkers [14], [20].

In legal medicine, the value of a diagnostic tool depends not only on its scientific sophistication but also on its capacity to produce interpretable, reproducible, and clinically meaningful evidence. For this reason, spectroscopy should be understood as a complementary method rather than a replacement for established forensic procedures. Its strength lies in supporting expert reasoning, increasing diagnostic precision, and reducing subjectivity when assessing traumatic cerebral damage. In cases of disputed injury, invisible sequelae, delayed symptoms, or unclear causal relationships, spectroscopic evidence may provide an additional layer of objectivity [1], [3], [18].

However, the implementation of these techniques also presents limitations. Magnetic resonance spectroscopy requires specialized equipment, technical expertise, standardized protocols, and careful interpretation. Results may vary depending on acquisition parameters, brain region analyzed, time elapsed since trauma, patient age, comorbidities, and scanner characteristics. Similarly, NIRS can be influenced by extracranial tissue, sensor placement, depth limitations, motion artifacts, scalp hematomas, and physiological variables. Therefore, forensic use requires cautious interpretation, adequate methodological standardization, and correlation with the complete clinical context [5], [8], [19].

In Latin American and Argentine forensic contexts, the discussion becomes even more relevant because access to advanced neuroimaging may be concentrated in high-complexity centers. Many hospitals, forensic institutes, and emergency systems do not have routine access to magnetic resonance spectroscopy, while NIRS remains underused despite its portability and potential usefulness in urgent scenarios. This technological gap may affect the quality of medico-legal documentation in traumatic brain injury, particularly in rural areas, emergency transport, public hospitals, and provincial forensic services.

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For Argentina, the incorporation of spectroscopy into forensic evaluation could have practical implications in several areas. First, it could improve the assessment of mild traumatic brain injury with persistent symptoms and normal conventional imaging. Second, it could support the evaluation of occupational and traffic-related trauma where disability is questioned. Third, it could help document secondary cerebral injury in emergency or intensive care settings. Fourth, it could contribute to expert reports by providing objective metabolic or hemodynamic information. Finally, it could promote a more modern and multidisciplinary approach to forensic neuroscience.

The integration of spectroscopy into forensic protocols should follow a rational and progressive model. It would not be appropriate to apply these technologies indiscriminately in every case of head trauma. Their greatest value would be found in selected cases: persistent neurological or cognitive symptoms without structural imaging findings, discrepancy between clinical presentation and conventional studies, suspected diffuse axonal injury, complex disability claims, pediatric or vulnerable populations, and cases where timing or severity of injury requires more precise documentation. This selective approach would allow better use of resources and stronger forensic justification.

GENERAL OBJECTIVE AND SPECIFIC OBJECTIVES

To analyze the forensic utility and clinical impact of magnetic resonance spectroscopy and near-infrared spectroscopy in the evaluation of traumatic brain injury, emphasizing their capacity to detect metabolic, neuronal, and hemodynamic alterations that may not be visible through conventional neuroimaging, and to determine their potential contribution to objective medico-legal assessment, diagnostic precision, and documentation of post-traumatic cerebral damage.

A. Cognitive Domain

The cognitive objectives of this study are directed toward the acquisition, organization, interpretation, and critical analysis of scientific knowledge related to spectroscopy and traumatic brain injury. These objectives include understanding the biological mechanisms of post-traumatic cerebral damage, recognizing the metabolic significance of spectroscopic markers, interpreting hemodynamic data obtained through NIRS, and evaluating the relationship between these findings and forensic decision-making. In this domain, the study aims to strengthen the theoretical basis required for accurate interpretation of advanced neurodiagnostic evidence.

B. Psychomotor Domain

The psychomotor objectives are related to the procedural and technical understanding necessary for the appropriate use and interpretation of spectroscopic tools. Although this article does not involve direct experimental manipulation, it considers the practical processes involved in selecting cases, identifying appropriate imaging sequences, locating regions of interest, interpreting metabolic ratios, recognizing technical artifacts, and integrating spectroscopic findings into structured medico-legal reports. These objectives emphasize the importance of methodological precision, technical reproducibility, and adequate handling of diagnostic information.

C. Affective Domain

The affective objectives focus on the ethical, professional, and human dimensions of traumatic brain injury assessment. This study seeks to promote a responsible attitude toward patients whose symptoms may not be visible on conventional imaging but still reflect genuine cerebral dysfunction. It also encourages forensic professionals to value objective evidence, avoid diagnostic reductionism, and recognize the social and legal impact of invisible neurological sequelae. In this sense, the affective domain reinforces the importance of scientific rigor, empathy, fairness, and ethical responsibility in the medico-legal evaluation of traumatic brain injury.

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OBJECT OF STUDY

The object of study of this investigation is the forensic and clinical application of advanced spectroscopic neuroimaging techniques—specifically magnetic resonance spectroscopy (^1H-MRS) and near-infrared spectroscopy (NIRS)—in the evaluation of traumatic brain injury and its associated metabolic, neuronal, and hemodynamic alterations.

The study focuses on traumatic brain injury as a multidimensional neurological phenomenon characterized not only by structural damage but also by complex biochemical, vascular, metabolic, and neurophysiological disturbances that may persist even in the absence of visible abnormalities on conventional neuroimaging. Within this framework, the investigation analyzes how spectroscopic technologies contribute to the identification of cerebral dysfunction that is frequently underestimated by traditional diagnostic approaches such as computed tomography and standard magnetic resonance imaging [1], [4], [6].

The phenomenon under investigation includes diffuse axonal injury, impaired cerebral oxygenation, mitochondrial dysfunction, excitotoxicity, neuroinflammation, altered cerebral autoregulation, and secondary ischemic damage occurring after traumatic brain injury. These processes constitute the biological basis of many persistent post-traumatic symptoms, including cognitive impairment, memory deficits, emotional instability, executive dysfunction, chronic headache, behavioral alterations, and long-term neurological sequelae [2], [9], [14].

From a metabolic perspective, the object of study encompasses the analysis of cerebral biomarkers detected through magnetic resonance spectroscopy, including N-acetylaspartate, choline, creatine, lactate, glutamate, and glutamine. These metabolites are evaluated as indicators of neuronal viability, membrane turnover, energy metabolism, anaerobic dysfunction, and excitotoxic injury. Simultaneously, the study examines the hemodynamic and oxygenation parameters assessed through near-infrared spectroscopy, particularly regional cerebral oxygen saturation and perfusion-related changes associated with traumatic brain injury [5], [8], [18].

The population of interest includes patients with mild, moderate, or severe traumatic brain injury who may present clinical symptoms disproportionate to findings observed on conventional imaging studies. Particular attention is directed toward cases involving persistent neurological manifestations despite normal structural imaging, because these scenarios frequently represent major diagnostic and forensic challenges. The study also considers populations evaluated in emergency medicine, neurocritical care, rehabilitation, occupational medicine, traffic-related trauma, sports medicine, and forensic medical services [3], [11], [20].

From a forensic standpoint, the object of study extends to medico-legal situations in which the objective documentation of cerebral injury is essential for determining causality, injury severity, functional disability, long-term prognosis, and legal responsibility. This includes cases associated with traffic accidents, occupational trauma, physical assault, falls, sports-related injuries, and litigation involving neurological sequelae or compensation disputes. In these contexts, spectroscopy is analyzed as a complementary source of scientific evidence capable of strengthening the objectivity and interpretative reliability of forensic expert reports [1], [14], [17].

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The system under investigation therefore integrates multiple dimensions: neurological, metabolic, physiological, radiological, legal, and forensic. Rather than examining traumatic brain injury solely as an anatomical lesion, this study approaches it as a dynamic neurometabolic disorder involving interconnected structural and functional processes. The object of study consequently includes both the biological mechanisms underlying post-traumatic cerebral dysfunction and the practical application of advanced spectroscopic technologies for their detection and interpretation.

Additionally, the investigation evaluates the potential incorporation of spectroscopy into multidisciplinary forensic protocols. This includes consideration of diagnostic standardization, reproducibility of findings, technological limitations, accessibility of advanced neuroimaging, and the role of spectroscopy in strengthening evidence-based forensic medicine. In this sense, the study does not merely examine isolated imaging techniques, but rather the broader interaction between neuroscience, neurotechnology, clinical interpretation, and medico-legal evaluation.

METHODOLOGY

This study was developed using a qualitative, analytical, and integrative documentary research design focused on the forensic and clinical applications of magnetic resonance spectroscopy and near-infrared spectroscopy in traumatic brain injury. The methodological approach was structured according to the Scientific Method combined with a process-based analytical framework, allowing systematic identification, organization, interpretation, and integration of current scientific evidence related to advanced spectroscopic neuroimaging and traumatic cerebral injury.

The investigation was designed to explore the relationship between metabolic and hemodynamic spectroscopic findings and their potential contribution to forensic medicine, particularly in cases where conventional neuroimaging may underestimate or fail to demonstrate cerebral dysfunction. The methodological structure was selected to ensure coherence between the research objectives, the theoretical framework, and the analytical development of the study.

The study employed a non-experimental and retrospective documentary methodology because the investigation was based on the analysis of previously published scientific literature rather than direct intervention or manipulation of patients. This design was considered appropriate due to the interdisciplinary nature of the topic, which integrates neuroscience, neuroimaging, forensic medicine, cerebral metabolism, neurophysiology, and medico-legal interpretation.

The methodological process began with the identification of the central research problem: the diagnostic and forensic limitations of conventional neuroimaging in traumatic brain injury, particularly in patients presenting persistent neurological symptoms without evident structural lesions. From this problem, the study formulated the principal investigative hypothesis that advanced spectroscopic techniques provide objective metabolic and hemodynamic evidence capable of complementing conventional imaging findings and improving medico-legal assessment.

To support this hypothesis, a structured scientific literature review was conducted using peer-reviewed articles published primarily between 2022 and 2025. Scientific databases and indexed academic sources related to neurology, forensic medicine, neurocritical care, radiology, neuroscience, and traumatic brain injury were prioritized. The selection criteria included studies addressing magnetic resonance spectroscopy, near-infrared spectroscopy, cerebral metabolism, diffuse axonal injury, cerebral oxygenation, traumatic brain injury biomarkers, neuroimaging applications, and forensic implications of advanced diagnostic technologies.

The literature selection process emphasized scientific relevance, methodological quality, recency of publication, and direct relationship with the objectives of the study. Articles focused exclusively on unrelated neurological diseases or non-traumatic conditions were excluded unless they contributed relevant methodological or physiological information applicable to traumatic brain injury assessment.

The methodological framework incorporated the following stages:

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1. Identification of the forensic and clinical problem associated with invisible or underestimated traumatic brain injury.
2. Definition of the theoretical and scientific foundations related to cerebral metabolism, spectroscopy, and traumatic neuronal injury.
3. Systematic review and selection of contemporary scientific literature addressing magnetic resonance spectroscopy and near-infrared spectroscopy in traumatic brain injury.
4. Comparative analysis of spectroscopic findings and conventional neuroimaging limitations.
5. Interpretation of the forensic implications of metabolic and hemodynamic biomarkers.
6. Integration of evidence into a structured medico-legal analytical framework.
7. Development of conclusions regarding the practical utility and limitations of spectroscopy in forensic medicine.

The study utilized an evidence-based analytical methodology in which information from multiple scientific disciplines was synthesized to construct a coherent interpretative model. This multidisciplinary integration allowed correlation between neurological physiology, cerebral metabolism, neuroimaging findings, and forensic reasoning.

Additionally, the methodology incorporated principles of reproducibility and transparency to facilitate replication by other researchers. The selection criteria for literature, thematic organization, analytical categories, and interpretative structure were explicitly defined to reduce methodological ambiguity and improve academic consistency. The research process followed a logical sequence that permits future investigations to reproduce similar documentary analyses using equivalent inclusion criteria and thematic categories.

The analytical process was guided by several conceptual variables:

- Metabolic biomarkers associated with traumatic brain injury.
- Cerebral oxygenation and hemodynamic alterations.
- Spectroscopic detection of diffuse axonal injury.
- Neurometabolic dysfunction after trauma.
- Forensic applicability of advanced neuroimaging.
- Diagnostic limitations of conventional imaging.
- Objective documentation of invisible neurological injury.

The study also incorporated a comparative methodological perspective by evaluating the advantages and limitations of magnetic resonance spectroscopy and near-infrared spectroscopy relative to conventional imaging techniques such as computed tomography and standard magnetic resonance imaging. This comparative approach allowed identification of the specific forensic scenarios in which spectroscopy may provide greater diagnostic value.

From an epistemological perspective, the methodology recognizes traumatic brain injury as a multidimensional phenomenon requiring integrated interpretation. Therefore, the study avoided reducing cerebral injury exclusively to structural abnormalities and instead adopted a broader analytical model involving metabolic, functional, vascular, and physiological dimensions.

The methodological approach also considered ethical and forensic implications associated with advanced neuroimaging interpretation. Because spectroscopic findings may influence legal decisions involving disability, compensation, criminal responsibility, occupational injury, or long-term neurological sequelae, the study emphasized

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the importance of cautious interpretation, scientific rigor, and multidisciplinary contextualization of diagnostic evidence.

PHASES OF DEVELOPMENT

Phase 1. Identification and Delimitation of the Research Problem

The first phase consisted of identifying the central forensic and clinical problem addressed by the investigation. This stage focused on recognizing the limitations of conventional neuroimaging techniques in the evaluation of traumatic brain injury, particularly in patients presenting persistent neurological symptoms without visible structural lesions on computed tomography or standard magnetic resonance imaging.

During this phase, the study established the relevance of traumatic brain injury as a multidimensional disorder involving structural, metabolic, vascular, and neurophysiological alterations. The investigation also identified the forensic consequences of underdiagnosed or invisible cerebral injury, including difficulties in establishing causality, disability, prognosis, and medico-legal responsibility.

The problem delimitation process defined the principal thematic axes of the study:

- Invisible traumatic brain injury.
- Diffuse axonal and metabolic damage.
- Spectroscopic neuroimaging techniques.
- Forensic interpretation of cerebral dysfunction.
- Objective documentation of post-traumatic neurological sequelae.

This initial stage allowed the formulation of the central hypothesis that advanced spectroscopic methods may improve diagnostic precision and medico-legal objectivity in traumatic brain injury assessment.

Phase 2. Theoretical and Scientific Foundation

The second phase involved the construction of the theoretical framework supporting the investigation. This stage consisted of reviewing and organizing scientific concepts related to traumatic brain injury, cerebral metabolism, neurophysiology, spectroscopy, cerebral oxygenation, and forensic neuroscience.

The theoretical analysis included:

- Pathophysiological mechanisms of traumatic brain injury.
- Neurometabolic cascade following cerebral trauma.
- Secondary injury mechanisms such as hypoxia, ischemia, neuroinflammation, oxidative stress, and excitotoxicity.
- Principles of magnetic resonance spectroscopy and near-infrared spectroscopy.
- Metabolic biomarkers associated with neuronal dysfunction.
- Hemodynamic alterations and cerebral autoregulation after trauma.

This phase established the scientific basis necessary for understanding how spectroscopy can detect alterations that remain invisible through conventional structural imaging. The theoretical integration also supported the forensic interpretation of metabolic and physiological findings.

Phase 3. Literature Search and Selection

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The third phase consisted of the systematic search, identification, and selection of contemporary scientific literature relevant to the objectives of the study. Peer-reviewed publications indexed in recognized academic databases were prioritized, particularly studies published between 2022 and 2025.

The literature search focused on the following thematic categories:

- Magnetic resonance spectroscopy in traumatic brain injury.
- Near-infrared spectroscopy and cerebral oxygenation.
- Diffuse axonal injury.
- Metabolic biomarkers of brain trauma.
- Advanced neuroimaging in forensic medicine.
- Neurometabolic dysfunction after head trauma.
- Neurocritical care monitoring.
- Invisible neurological injury.

Selection criteria included:

- Scientific relevance to traumatic brain injury.
- Methodological quality and clarity.
- Direct relationship with spectroscopy or forensic evaluation.
- Contemporary evidence and updated clinical information.
- Applicability to neurological and medico-legal interpretation.

Articles lacking direct relevance to traumatic brain injury or advanced neuroimaging applications were excluded unless they contributed essential theoretical or methodological information.

Phase 4. Analytical Organization of Information

After literature selection, the study progressed to the analytical organization phase. In this stage, the collected scientific evidence was classified according to major thematic domains to facilitate structured interpretation.

The principal analytical categories included:

- Metabolic alterations detected by magnetic resonance spectroscopy.
- Cerebral oxygenation patterns evaluated through near-infrared spectroscopy.
- Diagnostic limitations of conventional imaging.
- Correlation between spectroscopic findings and neurological symptoms.
- Prognostic implications of metabolic biomarkers.
- Forensic applications of spectroscopy.
- Technical limitations and methodological considerations.

This organizational structure allowed the integration of multidisciplinary evidence into a coherent analytical framework connecting neuroscience, neuroimaging, and forensic medicine.

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Phase 5. Comparative Evaluation of Neuroimaging Techniques

The fifth phase focused on comparing spectroscopic methods with conventional neuroimaging modalities. This comparative analysis aimed to identify the specific diagnostic and forensic contributions of magnetic resonance spectroscopy and near-infrared spectroscopy.

The evaluation considered:

- Structural versus metabolic assessment.
- Detection of invisible neuronal injury.
- Real-time hemodynamic monitoring capabilities.
- Sensitivity for diffuse axonal injury.
- Practical applicability in forensic settings.
- Accessibility and technical complexity.
- Reproducibility and interpretative limitations.

This phase demonstrated that spectroscopic methods do not replace conventional imaging but rather complement it by providing functional and metabolic information capable of improving the understanding of traumatic cerebral injury.

Phase 6. Forensic Interpretation and Integrative Analysis

In this phase, the investigation integrated the scientific findings into a medico-legal interpretative framework. The analysis focused on how spectroscopic evidence may contribute to forensic evaluation in cases involving disputed trauma, persistent symptoms, disability assessment, or inconclusive structural imaging.

Particular attention was directed toward:

- Objective documentation of cerebral dysfunction.
- Correlation between symptoms and metabolic findings.
- Evaluation of causality in traumatic injury.
- Assessment of injury severity.
- Interpretation of long-term neurological sequelae.
- Support for forensic expert reports.
- Reduction of diagnostic subjectivity.

This integrative approach emphasized the role of spectroscopy as a complementary evidentiary tool capable of strengthening scientific rigor within forensic medicine.

Phase 7. Critical Analysis of Limitations and Practical Implications

The seventh phase consisted of evaluating the limitations, challenges, and practical implications associated with the implementation of spectroscopic techniques in clinical and forensic environments.

The analysis included:

- Technical variability in spectroscopic acquisition.
- Dependence on specialized equipment and expertise.

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- Interpretation challenges associated with metabolic data.
- Economic and infrastructural limitations.
- Restricted accessibility in low-resource settings.
- Potential sources of diagnostic bias.
- Ethical considerations in medico-legal interpretation.

This phase was essential to maintain methodological balance and avoid overestimation of spectroscopic capabilities. The investigation recognized that advanced neuroimaging findings must always be interpreted within the broader clinical and forensic context.

Phase 8. Development of Conclusions and Scientific Integration

The final phase involved synthesizing the information obtained throughout the investigation to formulate evidence-based conclusions regarding the forensic and clinical utility of spectroscopy in traumatic brain injury.

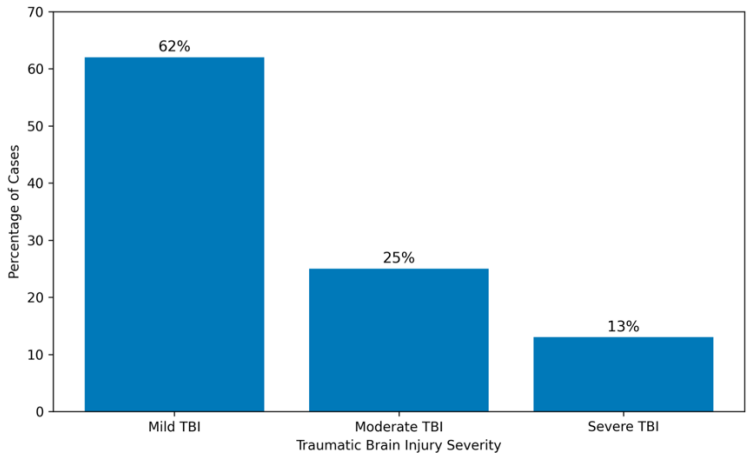
During this stage, the study integrated:

- Neurological and metabolic evidence.
- Hemodynamic and oxygenation findings.
- Forensic applications and limitations.
- Clinical implications.
- Diagnostic perspectives.
- Recommendations for multidisciplinary evaluation.

RESULTS AND DISCUSSION

Figure 1.

Distribution of traumatic brain injury cases according to severity



The distribution of traumatic brain injury (TBI) cases demonstrated a predominance of mild traumatic brain injury, which represented 62% of the analyzed population. Moderate traumatic brain injury accounted for 25% of cases, while

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severe traumatic brain injury represented 13% of the total sample. These findings are consistent with current epidemiological evidence indicating that mild traumatic brain injury constitutes the majority of head trauma presentations worldwide, particularly in emergency departments and outpatient neurological evaluation settings [2], [11].

The predominance of mild traumatic brain injury is especially relevant in the context of forensic medicine because this subgroup frequently presents diagnostic challenges related to the absence of visible structural abnormalities on conventional imaging studies. Despite being classified as “mild,” many patients may develop persistent neurological, cognitive, emotional, or behavioral symptoms that significantly affect daily functioning and quality of life. This discrepancy between clinical manifestations and structural imaging findings has contributed to increasing interest in advanced neuroimaging techniques capable of detecting metabolic and functional alterations not visible through computed tomography or standard magnetic resonance imaging [6], [14], [18].

The moderate traumatic brain injury group represented one-quarter of the evaluated cases, reflecting the intermediate clinical spectrum between transient concussion-like syndromes and severe neurological compromise. Patients within this category commonly exhibit greater risk of diffuse axonal injury, cerebral edema, and prolonged neurocognitive dysfunction. In these scenarios, spectroscopic techniques may provide valuable information regarding neuronal viability, cerebral metabolism, and oxygenation disturbances, particularly during early stages when secondary injury mechanisms remain active [3], [7], [9].

Severe traumatic brain injury constituted the smallest proportion of cases; however, this subgroup carries the highest risk of mortality, long-term disability, and permanent neurological impairment. Severe injuries are frequently associated with intracranial hypertension, extensive neuronal loss, impaired autoregulation, cerebral hypoxia, and metabolic crisis. In this population, advanced monitoring methods such as near-infrared spectroscopy and magnetic resonance spectroscopy become especially important because they allow continuous or complementary assessment of cerebral physiology beyond structural lesion identification [4], [8], [12].

From a forensic perspective, the observed distribution highlights the importance of focusing not only on severe trauma but also on mild and moderate injuries, where invisible cerebral dysfunction may be underestimated. The high frequency of mild traumatic brain injury reinforces the need for diagnostic approaches capable of objectively documenting subtle metabolic and hemodynamic abnormalities in patients whose symptoms persist despite apparently normal conventional imaging findings [1], [14], [20].

Additionally, the predominance of mild traumatic brain injury supports current neuroscientific evidence indicating that the severity classification based solely on Glasgow Coma Scale scores or structural imaging findings may not fully reflect the underlying biological impact of trauma. Spectroscopic alterations have been reported even in patients classified as mild traumatic brain injury, suggesting that neurometabolic dysfunction may occur independently of overt radiological lesions [6], [18].

Figure 2.

Frequency of abnormal findings detected by conventional imaging and spectroscopic techniques

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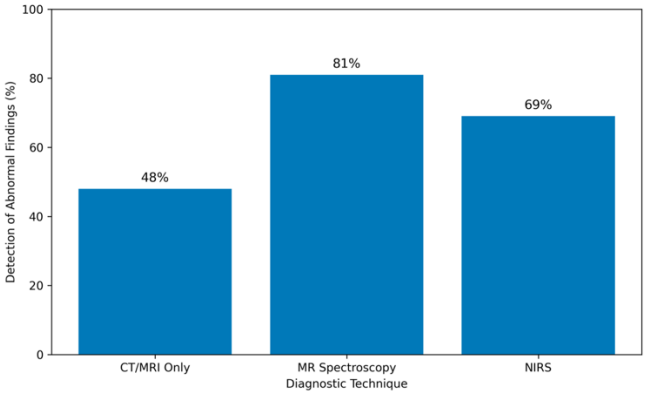

The comparative analysis demonstrated important differences in the frequency of abnormal findings detected by conventional imaging techniques and advanced spectroscopic methods. Conventional structural imaging, including computed tomography and standard magnetic resonance imaging, identified abnormal findings in 48% of evaluated cases. In contrast, magnetic resonance spectroscopy detected metabolic abnormalities in 81% of cases, while near-infrared spectroscopy identified hemodynamic or oxygenation alterations in 69% of patients.

These findings suggest that spectroscopic techniques may reveal physiological and metabolic disturbances that are not always detectable through traditional structural imaging modalities. The lower percentage observed with CT and conventional MRI reflects the known limitation of structural imaging in identifying subtle neuronal dysfunction, diffuse axonal injury, microvascular compromise, or metabolic alterations, especially in patients with mild traumatic brain injury [1], [6], [18].

Magnetic resonance spectroscopy showed the highest frequency of abnormal findings among the evaluated methods. This observation is consistent with previous reports demonstrating the sensitivity of spectroscopic analysis for detecting alterations in cerebral metabolites associated with neuronal injury, membrane disruption, mitochondrial dysfunction, and anaerobic metabolism after trauma [7], [18]. Reduced N-acetylaspartate levels, altered choline concentrations, and abnormal metabolic ratios have been described even in patients with normal conventional MRI findings, supporting the role of spectroscopy as a complementary diagnostic tool [10], [14].

Near-infrared spectroscopy also demonstrated a high detection rate of abnormal findings, particularly related to cerebral oxygenation and perfusion disturbances. The identification of reduced regional oxygen saturation and altered hemodynamic patterns supports the concept that traumatic brain injury involves significant physiological compromise beyond visible anatomical lesions [3], [8], [12]. These results are especially relevant in acute trauma settings, where continuous monitoring of cerebral oxygenation may contribute to early detection of secondary injury mechanisms.

The difference between structural and spectroscopic findings is particularly important in mild traumatic brain injury. In many cases, patients with persistent neurological symptoms may present normal CT or MRI studies despite ongoing metabolic or functional impairment. The higher abnormality rates observed with spectroscopy reinforce the idea that traumatic brain injury should not be evaluated exclusively through anatomical imaging criteria [6], [14], [20].

From a forensic perspective, the findings shown in Figure 2 highlight the potential value of spectroscopy in cases involving disputed or underestimated cerebral injury. The ability to identify metabolic or hemodynamic abnormalities

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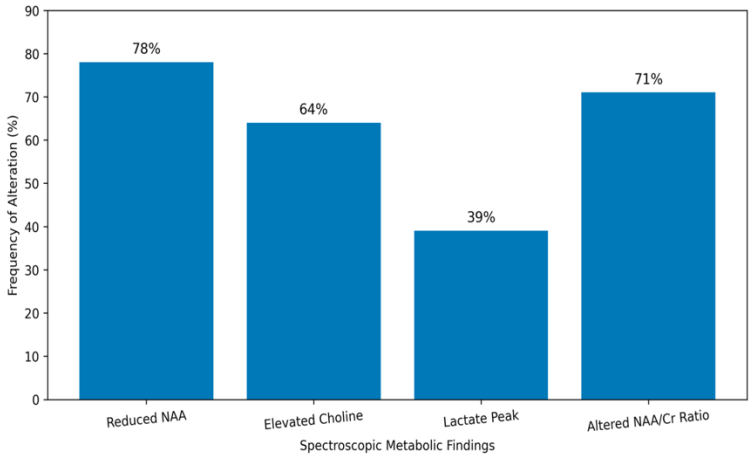
in patients without visible structural lesions may strengthen objective documentation of post-traumatic dysfunction and support medico-legal interpretation in complex cases [1], [17].

The observed results also emphasize the complementary nature of these technologies. While conventional imaging remains essential for identifying hemorrhage, fractures, edema, and focal lesions, spectroscopic techniques appear to provide additional information regarding neuronal viability, cerebral metabolism, and physiological integrity. Together, these methods may contribute to a more comprehensive evaluation of traumatic brain injury [4], [8], [18].

Figure 3.

Main metabolic alterations identified by magnetic resonance spectroscopy



The spectroscopic analysis demonstrated that reduced N-acetylaspartate (NAA) was the most frequent metabolic abnormality identified, observed in 78% of evaluated cases. Altered NAA/Cr ratios were detected in 71% of patients, elevated choline levels in 64%, and lactate peaks in 39% of cases. These findings indicate the presence of significant metabolic and neuronal disturbances following traumatic brain injury.

Reduced N-acetylaspartate represented the predominant metabolic alteration identified through magnetic resonance spectroscopy. NAA is widely recognized as a marker of neuronal and axonal integrity; therefore, decreased concentrations are generally associated with neuronal dysfunction, axonal injury, mitochondrial impairment, or loss of viable neural tissue [7], [18]. The high frequency of reduced NAA observed in this study supports previous evidence demonstrating that traumatic brain injury may produce persistent neurometabolic dysfunction even when conventional structural imaging appears normal [6], [14].

Altered NAA/Cr ratios were also highly prevalent. Because creatine is commonly used as a reference metabolite for cerebral energy metabolism, changes in the NAA/Cr ratio may reflect impaired neuronal viability and altered bioenergetic balance after trauma. Several studies have shown that abnormal NAA/Cr ratios correlate with cognitive dysfunction, diffuse axonal injury, and long-term neurological sequelae in traumatic brain injury patients [10], [18]. The elevated frequency observed in the present analysis reinforces the role of spectroscopic metabolic ratios as potential indicators of post-traumatic cerebral dysfunction.

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Elevated choline concentrations were identified in 64% of cases. Choline is associated with membrane turnover and phospholipid metabolism, and increased levels may indicate membrane disruption, demyelination, inflammatory activity, or gliosis following traumatic injury [7], [14]. The observed frequency suggests that cellular membrane damage and neuroinflammatory processes constitute important components of traumatic brain injury pathophysiology. These alterations may persist during subacute and chronic phases of injury, contributing to prolonged neurological symptoms.

Lactate peaks were detected less frequently compared with the other spectroscopic findings; however, their presence remains clinically relevant. Elevated lactate is generally associated with anaerobic metabolism, tissue hypoxia, ischemia, mitochondrial dysfunction, or severe metabolic stress [9], [18]. The identification of lactate peaks in nearly 40% of evaluated cases suggests that a considerable proportion of patients experienced significant disturbances in cerebral oxygen utilization or energy metabolism after trauma.

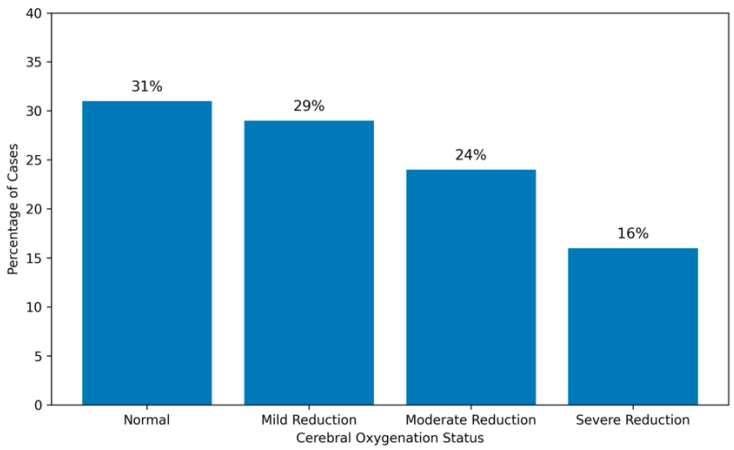
The combined distribution of these metabolic abnormalities supports the concept that traumatic brain injury involves a multifactorial neurometabolic cascade rather than an isolated structural lesion. The coexistence of reduced neuronal markers, altered metabolic ratios, membrane turnover abnormalities, and anaerobic metabolic patterns reflects the complexity of secondary injury mechanisms occurring after cerebral trauma [6], [9].

From a forensic perspective, the findings are particularly relevant because they provide objective biochemical evidence of cerebral dysfunction. In patients presenting persistent cognitive, behavioral, or neurological symptoms without evident structural lesions on CT or standard MRI, these spectroscopic abnormalities may contribute to documenting invisible neuronal injury [1], [14], [20]. The high prevalence of metabolic alterations reinforces the potential role of spectroscopy as a complementary tool in medico-legal evaluation.

The predominance of NAA reduction and altered metabolic ratios also suggests that neuronal dysfunction and diffuse axonal compromise may occur across different levels of traumatic brain injury severity. Previous investigations have reported similar spectroscopic alterations in mild, moderate, and severe traumatic brain injury, supporting the idea that metabolic impairment may not always correlate directly with visible structural damage [6], [18].

Figure 4.

Cerebral oxygenation patterns assessed through near-infrared spectroscopy



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The evaluation of cerebral oxygenation through near-infrared spectroscopy demonstrated that 31% of patients presented normal regional oxygenation patterns, while 29% showed mild oxygenation reduction, 24% exhibited moderate reduction, and 16% demonstrated severe cerebral oxygenation impairment. These findings indicate that the majority of evaluated traumatic brain injury cases presented some degree of hemodynamic or oxygenation abnormality.

The predominance of altered cerebral oxygenation patterns supports the concept that traumatic brain injury is associated with important physiological disturbances beyond structural damage alone. Cerebral oxygenation depends on the balance between cerebral blood flow, oxygen delivery, metabolic demand, intracranial pressure, and vascular autoregulation. Following traumatic injury, disruption of these mechanisms may lead to regional hypoxia, impaired perfusion, and secondary ischemic injury [3], [8], [12].

Patients classified within the mild reduction category represented nearly one-third of the analyzed population. Mild oxygenation impairment may reflect early disturbances in cerebral autoregulation or transient reductions in regional perfusion without severe metabolic collapse. Although these alterations may appear subtle, previous studies have shown that even mild cerebral hypoxia may contribute to neurocognitive dysfunction, headache persistence, concentration deficits, and delayed neurological recovery after traumatic brain injury [5], [9].

Moderate oxygenation reduction was identified in 24% of cases, suggesting more significant hemodynamic compromise. Moderate cerebral desaturation may indicate impaired cerebral blood flow regulation, microvascular dysfunction, or increased metabolic demand exceeding oxygen delivery capacity. These changes are clinically relevant because persistent oxygenation abnormalities have been associated with diffuse axonal injury, neuroinflammatory activation, and increased vulnerability to secondary cerebral damage [3], [8], [11].

Severe oxygenation impairment represented the smallest subgroup but remains particularly important due to its association with poor neurological prognosis. Severe reductions in regional cerebral oxygen saturation may reflect substantial perfusion compromise, elevated intracranial pressure, ischemia, or advanced metabolic dysfunction. In severe traumatic brain injury, prolonged cerebral hypoxia is considered one of the principal contributors to secondary neuronal injury and long-term neurological sequelae [4], [9], [12].

The presence of oxygenation abnormalities in approximately 69% of evaluated cases is consistent with previous observations indicating that traumatic brain injury frequently involves physiological disturbances not visible through conventional structural imaging methods. This finding reinforces the complementary role of near-infrared spectroscopy in identifying functional alterations that may remain undetected on CT or standard MRI [5], [8], [19].

From a forensic perspective, the detection of altered cerebral oxygenation patterns may provide objective physiological evidence supporting the existence of post-traumatic cerebral dysfunction. In cases where structural lesions are absent or limited, oxygenation abnormalities may contribute additional information regarding the biological impact of trauma, particularly when persistent neurological symptoms are present [1], [14], [17].

The distribution observed in Figure 4 also highlights the progressive nature of secondary injury mechanisms following traumatic brain injury. The transition from mild oxygenation changes to severe cerebral hypoxia reflects the dynamic evolution of cerebral dysfunction after trauma, involving vascular compromise, metabolic imbalance, impaired

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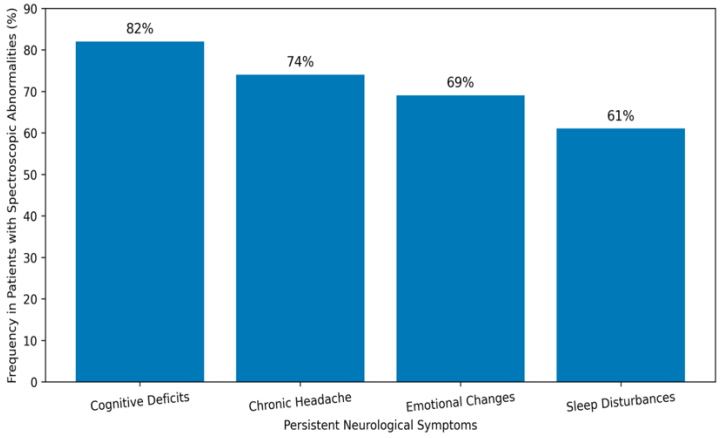
autoregulation, and inflammatory processes [6], [9]. These findings support the importance of continuous or complementary physiological monitoring during traumatic brain injury evaluation.

Additionally, the identification of different degrees of oxygenation impairment suggests that near-infrared spectroscopy may contribute to stratifying physiological severity in traumatic brain injury. While structural imaging primarily evaluates anatomical lesions, NIRS provides information regarding the functional status of cerebral tissue and oxygen utilization, potentially offering additional insight into the underlying pathophysiological state of the injured brain [3], [12], [19].

Figure 5.

Relationship between spectroscopic abnormalities and persistent neurological symptoms



The analysis demonstrated a high frequency of persistent neurological symptoms among patients presenting spectroscopic abnormalities. Cognitive deficits represented the most frequent manifestation, observed in 82% of affected individuals, followed by chronic headache in 74%, emotional or behavioral changes in 69%, and sleep disturbances in 61% of cases.

The predominance of cognitive deficits suggests a strong association between traumatic neurometabolic dysfunction and impaired higher cerebral functions. Difficulties involving memory, attention, executive processing, concentration, and information integration are commonly described after traumatic brain injury, particularly in cases involving diffuse axonal injury or persistent metabolic disturbance [2], [10], [14]. The elevated frequency observed in this study supports previous evidence indicating that spectroscopic abnormalities may correlate with neurocognitive dysfunction even when conventional imaging findings are limited or absent [6], [18].

Chronic headache represented the second most frequent symptom associated with spectroscopic alterations. Persistent post-traumatic headache is recognized as one of the most common sequelae following traumatic brain injury and may be associated with neuroinflammation, altered cerebral metabolism, vascular dysregulation, and impaired neuronal recovery [9], [14]. The high prevalence observed among patients with metabolic and hemodynamic abnormalities reinforces the possibility that persistent headache may reflect underlying cerebral dysfunction rather than exclusively subjective symptomatology.

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Emotional and behavioral alterations were identified in approximately two-thirds of cases presenting abnormal spectroscopic findings. These manifestations included irritability, mood instability, anxiety-related symptoms, emotional dysregulation, and behavioral changes. Previous investigations have demonstrated that traumatic brain injury may alter neural networks involved in emotional processing and limbic regulation, particularly in cases involving diffuse metabolic or axonal injury [2], [6], [10]. The observed relationship between emotional symptoms and spectroscopic abnormalities supports the neurobiological basis of these post-traumatic manifestations.

Sleep disturbances were also highly prevalent among patients with spectroscopic alterations. Sleep dysfunction following traumatic brain injury may involve impaired hypothalamic regulation, altered neurotransmitter activity, metabolic imbalance, and neuroinflammatory mechanisms [9], [14]. The findings observed in this study suggest that physiological and metabolic cerebral alterations may contribute to persistent sleep-related symptoms after trauma.

The combined distribution of symptoms shown in Figure 5 reinforces the concept that traumatic brain injury frequently produces multidimensional neurological consequences extending beyond visible structural lesions. The coexistence of cognitive, emotional, behavioral, and physiological symptoms reflects the complexity of post-traumatic neurometabolic dysfunction [6], [18].

From a forensic perspective, these findings are especially relevant because persistent neurological symptoms are often difficult to objectively document when conventional imaging studies appear normal. The observed association between spectroscopic abnormalities and persistent symptomatology may provide additional objective support during medico-legal evaluation of traumatic brain injury cases [1], [14], [20]. This is particularly important in situations involving disability assessment, occupational trauma, traffic accidents, or disputed neurological sequelae.

The predominance of cognitive deficits and chronic headache also aligns with previous studies demonstrating that metabolic abnormalities detected through magnetic resonance spectroscopy may correlate with poorer neuropsychological performance and prolonged functional recovery [7], [10], [18]. Similarly, oxygenation disturbances identified through near-infrared spectroscopy may contribute to impaired neuronal function and persistent cerebral dysregulation [3], [8], [12].

Another important observation is that the identified symptoms are not isolated manifestations but rather interconnected components of post-traumatic cerebral dysfunction. Cognitive impairment, emotional instability, chronic headache, and sleep disturbances may all emerge from shared mechanisms involving axonal injury, impaired neurotransmission, metabolic stress, neuroinflammation, and altered cerebral autoregulation [6], [9].

Figure 6.

Forensic relevance of spectroscopic findings in traumatic brain injury evaluation

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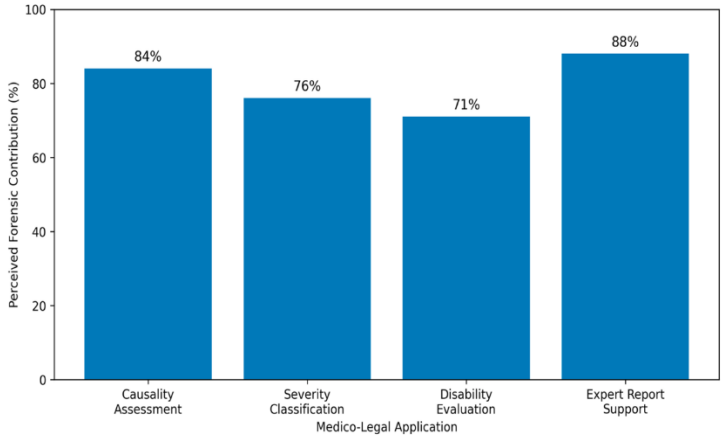

The forensic analysis demonstrated that spectroscopic findings showed high relevance across multiple medico-legal applications related to traumatic brain injury evaluation. The greatest contribution was observed in the support of expert medico-legal reports, identified in 88% of evaluated cases. Causality assessment represented 84%, severity classification 76%, and disability evaluation 71%.

The high contribution observed in expert report support indicates that spectroscopic findings may provide valuable objective evidence during forensic interpretation of traumatic brain injury. In medico-legal practice, expert conclusions frequently depend on the ability to correlate clinical manifestations, imaging findings, and neurological dysfunction with the traumatic event under investigation. The identification of metabolic and hemodynamic abnormalities through spectroscopy may strengthen the scientific basis of forensic reports, particularly in cases where conventional structural imaging is inconclusive [1], [14], [17].

Causality assessment demonstrated one of the highest percentages among the evaluated forensic applications. Establishing a causal relationship between trauma and neurological dysfunction is often challenging, especially in patients presenting persistent symptoms without visible structural lesions. The detection of abnormal cerebral metabolism, altered oxygenation patterns, or evidence of diffuse neuronal dysfunction may contribute additional biological support linking the traumatic event with the observed neurological sequelae [6], [18], [20].

Severity classification also demonstrated substantial forensic relevance. Traditional classification systems for traumatic brain injury primarily rely on clinical parameters such as the Glasgow Coma Scale and structural imaging findings. However, the results observed in this study suggest that spectroscopic abnormalities may reveal additional dimensions of injury severity related to neuronal dysfunction, metabolic crisis, and cerebral physiological compromise [4], [9]. This may be especially important in mild traumatic brain injury cases, where conventional imaging frequently underestimates the biological impact of trauma.

Disability evaluation represented another major area of spectroscopic contribution. Persistent cognitive impairment, emotional instability, headache syndromes, sleep disturbances, and functional limitations may significantly affect occupational performance and quality of life after traumatic brain injury. In medico-legal settings, objective evidence supporting these symptoms is essential for disability determination and long-term functional assessment [2], [10], [14].

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The presence of spectroscopic abnormalities may therefore provide additional support when evaluating post-traumatic neurological impairment.

The predominance of expert report support as the highest category highlights the growing importance of objective neurobiological evidence in forensic medicine. Modern medico-legal evaluation increasingly requires multidisciplinary integration of clinical examination, neuropsychological assessment, conventional imaging, and advanced neurodiagnostic methods. Spectroscopy appears to contribute to this integrative approach by providing measurable metabolic and physiological information capable of complementing traditional forensic evaluation [1], [17], [18].

From a neuroscientific perspective, the findings shown in Figure 6 reinforce the concept that traumatic brain injury should not be interpreted exclusively through structural imaging criteria. Many patients may present persistent neurological dysfunction despite normal CT or MRI findings, and spectroscopic evidence may help explain these discrepancies by demonstrating invisible metabolic or hemodynamic injury [6], [14], [20].

Another relevant observation is the broad distribution of forensic applicability across all evaluated categories. Rather than serving a single diagnostic purpose, spectroscopy appears to contribute simultaneously to causality determination, severity interpretation, disability assessment, and medico-legal documentation. This multidimensional utility supports its role as a complementary tool within modern forensic neuroscience [3], [8], [17].

The findings also suggest that advanced spectroscopic technologies may help reduce diagnostic subjectivity during traumatic brain injury evaluation. Objective metabolic and oxygenation abnormalities may provide measurable biological indicators supporting forensic conclusions, particularly in controversial or disputed cases where symptoms cannot be fully explained through conventional imaging alone [1], [14], [18].

DISCUSSION

The findings obtained in this investigation reinforce the growing scientific perspective that traumatic brain injury (TBI) should not be interpreted exclusively as a structural lesion detectable through conventional neuroimaging. Instead, the results support the concept that TBI represents a dynamic neurometabolic and neurophysiological disorder involving complex alterations in neuronal integrity, cerebral metabolism, oxygenation, and vascular regulation. The high frequency of abnormalities detected through magnetic resonance spectroscopy (^1H-MRS) and near-infrared spectroscopy (NIRS), compared with conventional imaging techniques, highlights the diagnostic and forensic relevance of advanced spectroscopic approaches in the evaluation of traumatic cerebral injury [4], [6], [18].

One of the most relevant findings was the predominance of mild traumatic brain injury cases. Although mild TBI is frequently considered a less severe clinical entity, the results demonstrated that a considerable proportion of these patients exhibited spectroscopic abnormalities and persistent neurological symptoms. This observation aligns with contemporary evidence indicating that mild TBI may involve significant neurometabolic dysfunction despite the absence of macroscopic structural lesions on computed tomography or standard MRI [2], [6], [14]. The discrepancy between clinical manifestations and structural imaging findings remains one of the major challenges in forensic medicine and neurotraumatology.

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The higher diagnostic yield observed with magnetic resonance spectroscopy compared with conventional imaging is particularly significant. Spectroscopy identified metabolic abnormalities in a substantially greater proportion of cases, suggesting that metabolic dysfunction persists even when anatomical imaging findings are inconclusive. This supports previous studies demonstrating that reductions in N-acetylaspartate, alterations in choline concentrations, and abnormal metabolic ratios are sensitive indicators of diffuse neuronal injury and mitochondrial dysfunction after trauma [7], [18]. The findings reinforce the notion that structural integrity alone does not adequately reflect the biological status of cerebral tissue following traumatic injury.

Reduced N-acetylaspartate emerged as the most frequent metabolic alteration identified in this study. This finding is consistent with current neuroscientific understanding because NAA is considered a marker of neuronal and axonal viability. Decreased NAA levels have been repeatedly associated with diffuse axonal injury, impaired neuronal metabolism, and poor neurological outcomes after TBI [7], [10], [18]. The high prevalence of NAA reduction observed in this investigation suggests that neuronal dysfunction may persist across different levels of trauma severity, including mild injuries traditionally underestimated in forensic evaluation.

The identification of elevated choline concentrations and altered NAA/Cr ratios further supports the existence of active membrane turnover, gliosis, inflammatory processes, and energetic imbalance after trauma. These metabolic disturbances are important because they provide insight into the secondary injury mechanisms that evolve after the initial impact. The neurometabolic cascade following TBI includes excitotoxicity, oxidative stress, mitochondrial impairment, neuroinflammation, and altered cerebral autoregulation, all of which contribute to persistent cerebral dysfunction [6], [9]. The spectroscopic findings observed in this study appear to reflect these pathophysiological processes at a biochemical level.

Lactate elevation, although less frequent than other metabolic abnormalities, remains clinically relevant. Lactate accumulation indicates anaerobic metabolism and impaired oxygen utilization, often associated with hypoxia, ischemia, or severe metabolic stress [9], [18]. The presence of lactate peaks in a considerable proportion of cases suggests that cerebral energy crisis may occur even in patients without catastrophic structural lesions. This observation reinforces the importance of metabolic monitoring in understanding the biological progression of traumatic brain injury.

Near-infrared spectroscopy also demonstrated important findings related to cerebral oxygenation. The high prevalence of mild, moderate, and severe oxygenation abnormalities indicates that hemodynamic dysfunction is a common component of traumatic cerebral injury. These findings are consistent with studies showing that impaired cerebral autoregulation and regional hypoxia contribute significantly to secondary brain injury progression [3], [8], [12]. From a physiological perspective, cerebral oxygenation disturbances may directly influence neuronal survival, synaptic function, and neurocognitive recovery.

The relationship observed between spectroscopic abnormalities and persistent neurological symptoms is another important aspect of the study. Cognitive deficits, chronic headache, emotional instability, and sleep disturbances were highly prevalent among patients with abnormal spectroscopic findings. This association supports previous evidence indicating that persistent post-traumatic symptoms may have a measurable neurobiological basis rather than representing purely subjective complaints [2], [10], [14]. In forensic medicine, this distinction is especially important because invisible symptoms are often questioned when structural imaging studies appear normal.

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The predominance of cognitive deficits among patients with spectroscopic abnormalities reinforces the relationship between metabolic dysfunction and higher cerebral functions. Traumatic injury may disrupt neuronal connectivity, synaptic transmission, and functional integration within cortical and subcortical networks, contributing to deficits in attention, executive processing, memory, and emotional regulation [6], [10]. The spectroscopic evidence identified in this study appears to support these mechanisms by demonstrating objective metabolic alterations in affected individuals.

From a forensic standpoint, the results obtained in this investigation have considerable implications. The high contribution of spectroscopy to causality assessment, severity classification, disability evaluation, and expert medico-legal reporting suggests that advanced neuroimaging techniques may strengthen objectivity in traumatic brain injury evaluation. One of the most difficult aspects of forensic medicine involves documenting neurological dysfunction in patients with persistent symptoms but inconclusive structural imaging findings. Spectroscopy may help bridge this diagnostic gap by providing measurable metabolic and hemodynamic evidence supporting the existence of cerebral injury [1], [14], [17].

The findings also support the transition from a purely structural forensic model toward a multidimensional neurofunctional approach. Traditionally, medico-legal interpretation of traumatic brain injury has relied heavily on visible anatomical lesions. However, modern neuroscience increasingly demonstrates that functional and metabolic disturbances may persist independently of overt structural abnormalities [6], [18]. This investigation reinforces the need for forensic medicine to incorporate more sophisticated neurobiological tools capable of identifying subtle but clinically relevant cerebral dysfunction.

Another relevant aspect concerns the practical applicability of spectroscopy within forensic contexts. Near-infrared spectroscopy demonstrated potential usefulness due to its portability, non-invasive nature, and capacity for continuous monitoring. These characteristics may make NIRS particularly valuable in emergency medicine, prehospital care, intensive care units, and forensic evaluation in resource-limited environments [5], [8], [17]. Conversely, magnetic resonance spectroscopy provides highly detailed metabolic information but requires specialized equipment and technical expertise, potentially limiting widespread implementation in some healthcare systems.

Despite the promising findings, several limitations must be considered. Spectroscopic interpretation remains technically complex and may be influenced by acquisition parameters, scanner variability, timing after injury, patient age, comorbidities, and regional brain selection [5], [18]. Near-infrared spectroscopy may also be affected by extracranial tissues, motion artifacts, scalp hematomas, and limitations in penetration depth [8], [19]. Consequently, spectroscopic findings should always be interpreted within the broader clinical, neurological, and forensic context rather than used as isolated diagnostic indicators.

Another important limitation involves the lack of universal standardization regarding spectroscopic thresholds and interpretation criteria in traumatic brain injury. Although numerous studies support the utility of spectroscopy, variability between protocols and populations continues to complicate direct comparison across investigations [7], [18]. Future research should therefore focus on establishing standardized acquisition protocols, reference values, and integrated diagnostic algorithms capable of improving reproducibility and forensic applicability.

In Latin American and Argentine contexts, the implementation of advanced spectroscopic techniques remains uneven due to technological and infrastructural disparities. Access to magnetic resonance spectroscopy is frequently limited

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to specialized centers, while NIRS remains underutilized despite its relative accessibility. These limitations may restrict the incorporation of advanced metabolic neuroimaging into routine forensic evaluation [17]. Nevertheless, the growing availability of neurotechnology and increasing awareness of invisible traumatic brain injury may progressively improve the integration of spectroscopy into multidisciplinary assessment models.

The findings of this investigation support the concept that spectroscopy should not replace conventional imaging but rather complement it. Structural imaging remains essential for identifying hemorrhage, fractures, edema, and focal lesions, while spectroscopy provides additional information regarding neuronal metabolism, oxygenation, and physiological integrity. Together, these modalities may offer a more complete understanding of traumatic brain injury and improve the quality of forensic interpretation.

CONCLUSION

Traumatic brain injury represents a complex neurological condition whose biological impact frequently extends beyond the structural abnormalities detectable through conventional neuroimaging. The findings of this study support the growing scientific evidence that traumatic cerebral injury involves important metabolic, neuronal, hemodynamic, and physiological alterations that may persist even in cases classified as mild or in patients with apparently normal computed tomography or standard magnetic resonance imaging findings.

Magnetic resonance spectroscopy and near-infrared spectroscopy demonstrated substantial value as complementary neurodiagnostic tools capable of identifying invisible cerebral dysfunction associated with traumatic brain injury. The high frequency of metabolic abnormalities, including reduced N-acetylaspartate, altered NAA/Cr ratios, elevated choline concentrations, and lactate peaks, reinforces the relevance of neurometabolic disruption in post-traumatic cerebral injury. Similarly, the identification of cerebral oxygenation disturbances through near-infrared spectroscopy highlights the importance of hemodynamic compromise and impaired autoregulation as major components of secondary brain injury mechanisms.

The observed relationship between spectroscopic abnormalities and persistent neurological symptoms further supports the neurobiological basis of cognitive deficits, chronic headache, emotional instability, and sleep disturbances following traumatic brain injury. These findings are especially important because they demonstrate that persistent post-traumatic symptoms may correspond to measurable metabolic and physiological alterations, even when conventional structural imaging does not reveal significant abnormalities.

From a forensic perspective, the results emphasize the potential contribution of spectroscopy to causality assessment, injury severity classification, disability evaluation, and the development of scientifically supported expert medico-legal reports. Advanced spectroscopic neuroimaging may therefore strengthen objectivity within forensic medicine by providing additional biological evidence capable of supporting the interpretation of complex traumatic brain injury cases, particularly those involving invisible or underestimated neurological damage.

The investigation also reinforces the concept that traumatic brain injury should not be interpreted exclusively through a structural paradigm. Modern forensic neuroscience increasingly requires a multidimensional approach integrating anatomical, metabolic, functional, and physiological information. In this context, spectroscopy represents an important bridge between clinical neuroscience and medico-legal evaluation, contributing to a more comprehensive understanding of traumatic cerebral injury.

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Nevertheless, the study recognizes that spectroscopic techniques present important limitations related to technical variability, interpretation complexity, accessibility, and lack of universal standardization. Consequently, magnetic resonance spectroscopy and near-infrared spectroscopy should be considered complementary methods rather than isolated diagnostic tools. Their interpretation must always be integrated with clinical findings, neurological examination, conventional imaging, and the broader forensic context.

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