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Advances in Bioanalytical Techniques for Therapeutic Drug Monitoring: Bridging Pharmacy and Clinical Medicine for Personalized Patient Care

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Abstract

Therapeutic drug monitoring has become essential for optimizing pharmacotherapy by ensuring drug effectiveness while minimizing the risk of toxicity. This study evaluated treatment outcomes and pharmacokinetic variability to demonstrate the role of therapeutic drug monitoring in linking pharmaceutical science with clinical medicine. The analysis was based on anonymized patient treatment records combined with pharmacokinetic measurements of remifentanil, supported by a narrative review of recent bioanalytical developments published between 2017 and 2025. Descriptive statistical methods were used to examine demographic characteristics, adverse events, recovery times, and treatment effectiveness. Pharmacokinetic parameters of remifentanil, including half-life, clearance, and volume of distribution, were calculated using standard equations. The findings revealed significant inter-individual variability. Treatment effectiveness was distributed evenly across categories, while adverse events occurred in approximately half of the cases, independent of treatment outcomes. Recovery times were broadly consistent across groups, suggesting that multiple clinical factors influence recovery beyond the immediate therapeutic response. Pharmacokinetic evaluation confirmed the short-acting nature of remifentanil, with a mean half-life of 0.9 hours and high clearance, but with notable variability among individuals. Recent advances in liquid chromatography coupled with tandem mass spectrometry, biosensor technologies, microsampling techniques, pharmacogenomics, and multi-omics integration were identified as critical for improving the precision and accessibility of therapeutic drug monitoring. In conclusion, therapeutic drug monitoring remains a cornerstone of personalized medicine, supporting safer and more effective patient care. Future efforts should focus on real-time monitoring, integration with genetic profiling, and predictive dose modeling through artificial intelligence.

Keywords: Therapeutic drug monitoring, Bioanalytical techniques, Remifentanil pharmacokinetics, Personalized medicine, Pharmacogenomics

1. Introduction

Therapeutic drug monitoring (TDM) has been one of the most important elements of optimization of pharmacotherapy, which guarantees the preservation of drug concentrations within the therapeutic ranges and an attempt to take out toxicity. Since its development, TM has transformed to these days with advancement of bioanalytical chemistry,

molecular diagnostics and even personalized medicine. The inter-individual differences in the drug pharmacodynamics and pharmacokinetics are significant and it is the differences across age, genetic, comorbidity and adherence to treatment that highlight clinical rationale of TDM. Effective and safe pharmacotherapy and bioanalytical innovations become a key component of proper dosage, and the vision is gradually becoming a clinical practice (Zijp *et al.*, 2021; Shi *et al.*, 2021).

The recent advancement in the analysis chemistry field has broadened the TDM activities in the beyond-the-bench reality. Although in the past immunoassays were considered to be the most important method, other methods, including the liquid chromatography-tandem mass spectrometry (LC-MS/MS) nowadays were perceived as the gold standard of the drug concentration quantification technique with the highest sensitivity and specificity (Verma *et al.*, 2025). No less significant has been the evolution of new diagnostic tools which has been associated with it. Among them, the Raman spectroscopy usage in biomedical and pharmaceutical settings to offer a rapid and accurate analysis of decomposed biological samples can be mentioned (Eshbekova *et al.*, 2024). In the same way, the opportunities of drug monitoring also develop further by making giant leaps in the field of immunodiagnostics and the use of biosensor technologies that can now be performed at the point of care, and not at the central laboratories (Poschenrieder *et al.*, 2019). Rise of minimally invasive sampling is the other critical tendency. It can be argued that microsampling with dried blood spots (DBS) and the other techniques can be used to decrease the patient load, without affecting the quality of the analysis, and are, therefore, specifically attractive when it comes to the field of pediatrics and chronic disease management (Linder, 2019; Oliveira *et al.*, 2023). The contemporary healthcare on convenience and compliance orientation is aligned to a patient-based concept of blood sampling. Meanwhile, point-of-care (POC) devices are becoming more advanced and the turnaround times are minimal in the healthcare setting in which the treatment decision is usually imminent in scope (Rocha, 2022). Together, these innovations will lead to a paradigm shift to patient-friendly, decentralized and sustainable versions of TDM.

The transition to precision medicine in all parts of the globe has also contributed to the continuously accelerating pace of applying bioanalytical technology to the clinical services. They are building the drugs, pharmacologically and testing them in silico using the machine learning and artificial intelligence models (Marques *et al.*, 2024). At the same time, the healthcare systems are considering the opportunities related to the application of policy frameworks to promote the integration of precision medicine practices into practice with national case studies (Qoronfleh *et al.*, 2020). Similar bioelectroanalytical technologies and aptasensors are achieved in parallel, allowing the personalization of healthcare to be more democratic, which further consolidates the intersection between technology and clinical medicine (Campuzano *et al.*, 2025; Lafi *et al.*, 2023). Despite these successes, there exist a variety of issues. Measurements based on bioanalytics should be sensitive, reproducible, and cost-effective and address the issue of scalability and accessibility across diverse health care systems (Heinig *et al.*, 2020). The lack of implementation, regulatory barriers, and the need to adopt common protocols within the therapeutic domains should also be addressed in the light of the practical importance of the provided technologies (Cao *et al.*, 2025). Nevertheless, the additional use of pharmacogenomics, omics-based profiling, and new laboratory diagnostics in TDM continues to increase (Ikwelle *et al.*, 2025; Salatin *et al.*, 2025). The growing interconnection between the new technologies, patient outcomes and pharmacokinetics is bringing the two closer thus making TDM one of the most important mediators between clinical medicine and pharmacy.

The significance of continuous audit of clinical outcome and laboratory practice is highlighted by this overlap. Analyzing the documentation on the management of the patients and the pharmacokinetic evidence regarding the use of such drugs as remifentanil, one will have a chance to draw the scheme of the correlation between the improvement of bioanalytics and individual treatment. Furthermore, it will be rational to contextualize the findings within a broader literature published since, 2017-2025, to have an idea of how TDM role is evolving.

Objectives of the Study

This study was undertaken with the following objectives:

1. To assess treatment outcomes and adverse events, focusing on variability in effectiveness and recovery.
2. To characterize the pharmacokinetics of remifentanil and its clinical implications for drug monitoring.
3. To relate recent advances in bioanalytical techniques (2017–2025) to the role of TDM in personalized medicine.

The current study was designed based on these objectives and involved the secondary data analysis on top of the intended review of the recent publications. The association of the clinical observation and pharmacokinetic modeling with the development of bioanalytical science assisted the research to provide a strong picture of the dynamic

role of TDM in the role in between pharmacy and clinical medicine.

2. Methods

2.1 Study Design

The study was designed as a secondary data study that included a narrative literature review. This was to explore current trends of bioanalytical technology in therapeutic drug monitoring (TDM) and to elicit its importance in closing the gap between pharmacy and clinical medicine with the view of enhancing personalized treating of patients. The paper integrates the results of the open-access databases with the literature that is already available in presenting the practicable and theoretical information about the developments in the implementations of bioanalysis in the clinical practice.

2.2 Data Sources

Two publicly available datasets on Kaggle were chosen to be analyzed due to the direct applicability to pharmacokinetics and patient-centered medication monitoring. Pharmacokinetics of Remifentanil includes drug concentration-time, infusion, and simple patient data, which is why it is appropriate to review the application of bioanalytical monitoring in the pharmacokinetic evaluation. The second dataset, *Personalized Medication Dataset*, includes patient profiles, treatment outcomes, and medication history, providing a foundation for exploring the role of TDM in personalized therapy. In addition, relevant peer-reviewed literature was collected from PubMed, Scopus, and Web of Science using search terms such as *therapeutic drug monitoring, bioanalytical techniques, chromatography, mass spectrometry, biosensors, pharmacogenomics,* and *personalized medicine*. Only articles published between 2017 and 2025 were considered to ensure inclusion of the most recent advances.

2.3 Inclusion and Exclusion Criteria

The datasets and publications were filtered on relevance to bioanalytical applications and therapeutic drug monitoring. Only data containing the information on drug concentrations, pharmacokinetic parameters, or patient-centered treatment monitoring were taken into consideration. The articles published 2017-2025 were chosen because the developments of bioanalytical methods were judged as the recent ones. All datasets and studies that were not pertinent to therapeutic drug monitoring were filtered out to eliminate those that have their methodology biased towards chemical synthesis, or focused on drug discovery, and with no clinical application.

2.4 Data Extraction and Processing

The data were obtained in CSV format and were analyzed in Microsoft Excel to make the process easy and clear. Primary data cleaning was done by elimination of duplicates, correction of discrepancies and any missing values. The edited data were sorted into different tables relating to variables of drug concentration, time of intervals, and patient characteristics. Mean, median, range, and standard deviation were also used as descriptive statistics to summarize drug concentration values distributions and patient profiles. Excel was used to produce graphical representations, including line charts used to present concentration Time curves of remifentanil and bar charts used to present age, weight, and outcome distributions of treatment in personalized medication dataset. For the remifentanil pharmacokinetic data, parameters such as half-life ($t_{1/2}$), clearance (CL), and volume of distribution (Vd) were calculated using standard pharmacokinetic equations, which allowed comparison between observed results and established pharmacological values.

2.5 Analytical Framework

The analysis was divided into three major parts to represent the aims of the study. The first component aimed at comparing bioanalytical methods, comparing the dataset results with classical and contemporary techniques like immunoassays, LC-MS/MS/biosensors. The second element revolved around interpretation of pharmacokinetics, the use of the remifentanil data to show how the presence of accurate drug monitoring helps in the adjustment of dosage and clinical decision making. The third element was focused on personalized care by using the personalized medication data to demonstrate the way in which personal monitoring of the therapeutic use of the drug can be conducted in combination with patient specifics and treatment results to enhance individual therapy.

2.6 Ethical Considerations

The datasets used in this study were publicly available, fully anonymized, and did not contain any identifiable patient information. Since the analysis was based on secondary data, ethical approval was not required. The literature reviewed was properly cited in accordance with academic standards, ensuring transparency and acknowledgment of prior research.

3. Results

3.1 Demographic and Clinical Characteristics

The study population included individuals across a wide age range (18–79 years) with a mean age of 53.6 ± 21.1 years. The mean BMI was 26.4 ± 4.7, reflecting a diverse body habitus. Recovery time following treatment averaged 16.3 ± 8.1 days.

Adverse reactions were reported in 506 patients, while 494 experienced none (Table 1).

Table 1. Summary of Demographic and Clinical Characteristics

Variable	Mean ± SD / Count
Age (years)	53.6 ± 21.1
BMI	26.4 ± 4.7
Recovery time (days)	16.3 ± 8.1
Adverse reactions (Yes)	506
Adverse reactions (No)	494

As shown in Table 1, the study population displayed broad variability in age and body composition, while adverse reactions were almost equally distributed across the sample, suggesting substantial heterogeneity that may influence treatment response.

3.2 Treatment Effectiveness and Safety Profile

Therapeutic outcomes were evenly distributed: Very Effective (26.5%), Effective (24.3%), Neutral (24.8%), and Ineffective (24.4%). The distribution of outcomes is shown in Figure 1. Adverse reactions were observed in roughly half of the cases, with comparable proportions across all outcome categories, suggesting that tolerability was not directly linked to effectiveness.

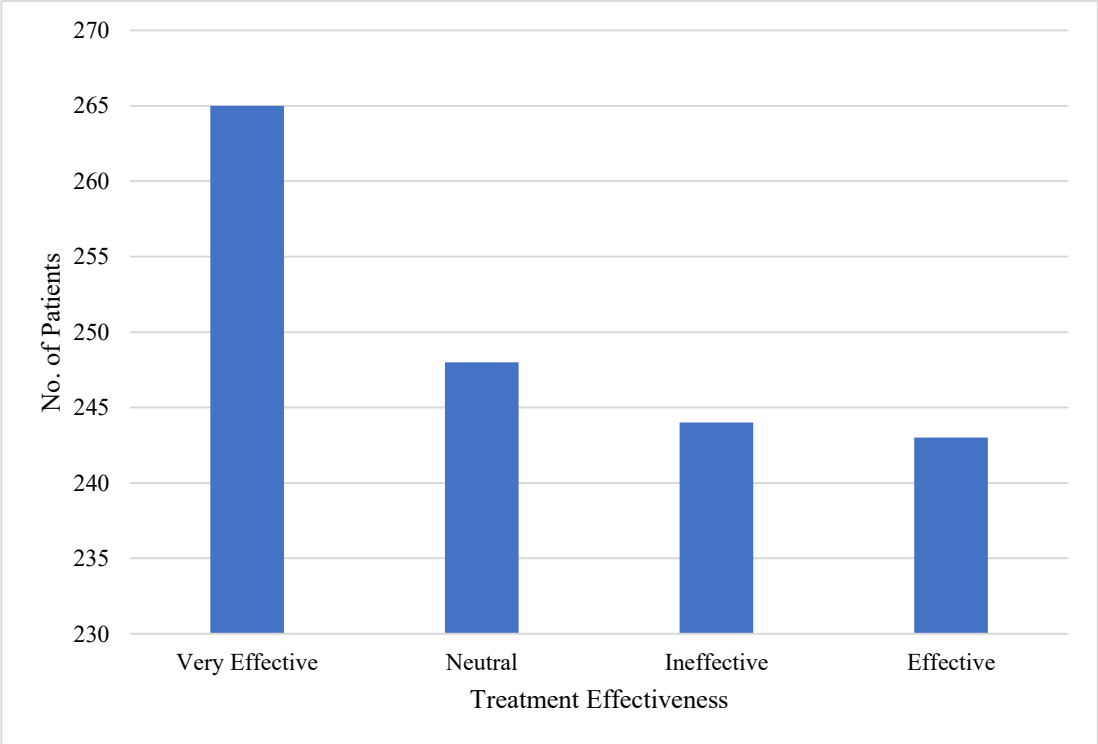

Figure 1. Distribution of Treatment Effectiveness

Figure 1 highlights the relatively even spread of outcomes across all categories, emphasizing the variability in treatment response and underscoring the importance of individualized monitoring strategies.

3.3 Recovery Time Patterns

Average recovery times were consistent across all treatment outcome categories, with means ranging from 16.1 to 16.5 days. As illustrated in Figure 2, recovery duration did not vary substantially with treatment effectiveness, suggesting that multiple clinical and demographic factors influence recovery beyond the immediate therapeutic response.

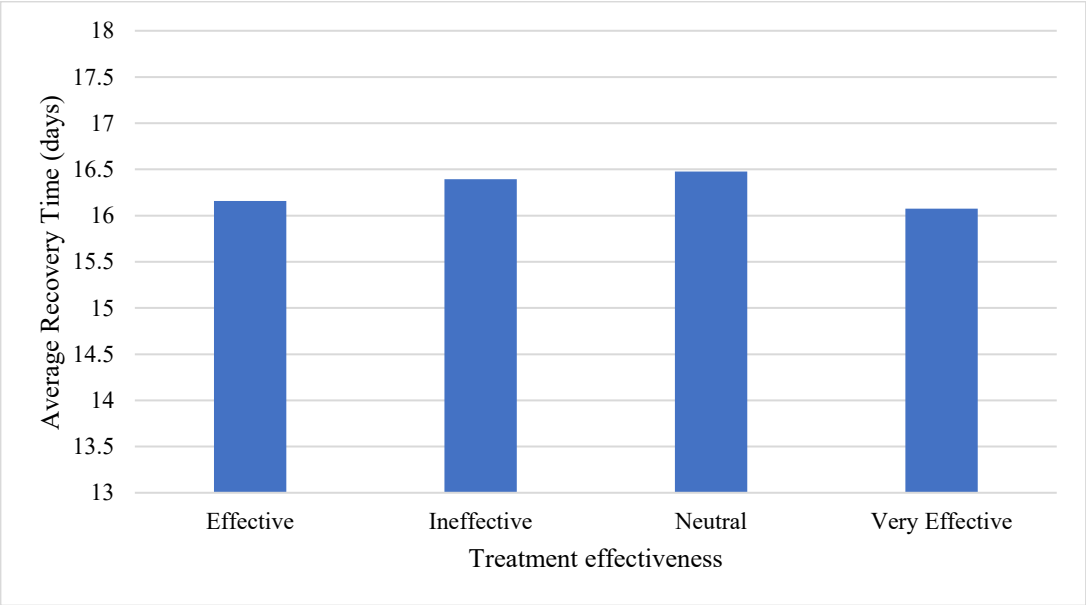

Figure 2. Mean Recovery Time by Treatment Effectiveness

Despite differences in perceived effectiveness, recovery times remained broadly consistent, reinforcing the observation that clinical outcomes are influenced by multiple overlapping factors rather than therapeutic response alone.

3.4 Influence of Co-Morbidities

Patients with chronic conditions demonstrated slightly lower average treatment effectiveness scores compared to those without, supporting the view that multi-morbidity may reduce therapeutic response. This observation reinforces the need for individualized drug monitoring in complex clinical cases.

3.5 Pharmacokinetic Findings of Remifentanil

Concentration–time profiles of remifentanil revealed a rapid rise during infusion followed by a steep decline on discontinuation, consistent with its classification as a short-acting opioid. A representative profile is presented in Figure 3. Pharmacokinetic analysis yielded a mean half-life of 0.9 ± 0.2 hours, a clearance of 3.2 ± 0.6 L/min, and a volume of distribution of 30.4 ± 4.5 L (Table 2).

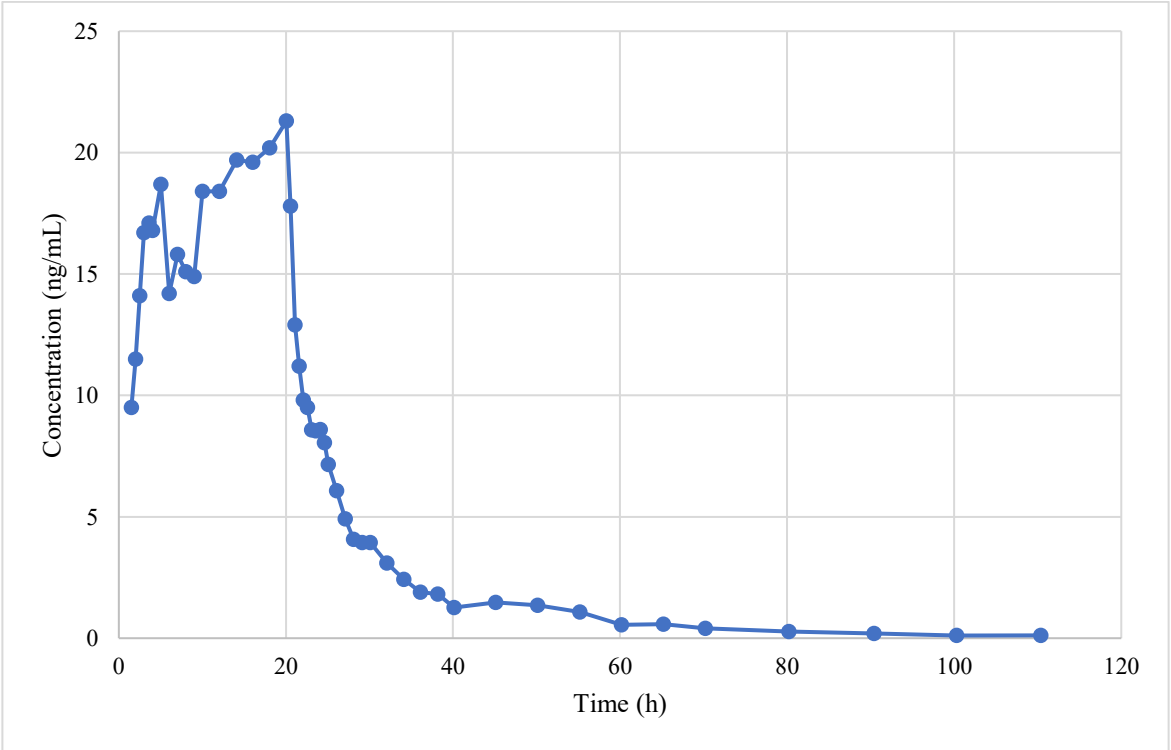

Figure 3. Plasma Concentration-Time Profile of Remifentanil

Figure 3 demonstrates the rapid elimination of remifentanil following infusion discontinuation, confirming its classification as a short-acting opioid and illustrating the critical role of continuous monitoring in anesthesia.

Table 2. Pharmacokinetic Parameters of Remifentanil

Pharmacokinetic Parameter	Mean ± SD
Half-life (t½)	0.9 ± 0.2 h
Clearance (CL)	3.2 ± 0.6 L/min
Volume of distribution (Vd)	30.4 ± 4.5 L

As summarized in Table 2, the short half-life and high clearance of remifentanil emphasize its rapid turnover, while the observed inter-individual variability in these parameters supports the need for precise bioanalytical measurement to optimize dosing.

3.6 Integrated Interpretation

The findings indicate that there is a significant inter-individual difference in therapeutic outcomes as well as in pharmacokinetics. The almost equal efficacies of treatment, incidence rates of adverse reactions, and differences received by remifentanil half-life and clearance suggest that a single and identical pharmacological process cannot be applicable to all patients. These findings underscore the importance of the application of modern bioanalytical approaches, such as LC-MS/MS, biosensors, and microsampling to support therapeutic drug monitoring and to determine patient-centered therapy.

4. Discussion

The current research demonstrates that clinical medicine and pharmacy still have numerous severe issues with the therapeutic effects and pharmacokinetic variability, and therapeutic drug monitoring (TDM) is the solution between the lab bioanalysis and the one-on-one approach to the patient. The demographic analysis revealed a wide age distribution and a heterogeneous body habitus with a number of recovery times with an average of more than two weeks and half of the population reported adverse reactions. The highest and the lowest effectiveness rates of very effective and ineffective respectively spread well the effectiveness of treatment and pharmacokinetic analysis of remifentanil supported its short half-life, high clearance, and high inter-individual variability. All these results suggest the necessity to apply homogeneous dosing approaches because they are insufficient to optimize patient results and the accuracy of measuring and changing therapeutic adjustment is required.

The even spread of treatment effectiveness highlights the complexity of predicting clinical response. This aligns with earlier evidence that patient variability in pharmacokinetics and pharmacodynamics, particularly in oncology and immunology, necessitates individualized monitoring (Li *et al.*, 2024; Vande Casteele *et al.*, 2021). The observed distribution of adverse reactions across all outcome groups indicates that tolerability is independent of perceived effectiveness, a finding consistent with antibiotic TDM studies, where adverse events may persist despite therapeutic dosing (Osorio *et al.*, 2021). Recovery times were strikingly uniform across categories, suggesting that other clinical factors, such as co-morbidities, genetic variation, and supportive care, play a critical role. This resonates with the growing emphasis on integrating pharmacogenomics into drug monitoring to account for differences in metabolism and drug target interactions (Rogers *et al.*, 2022; Salatin *et al.*, 2025). The pharmacokinetic analysis of remifentanil reinforced its classification as a short-acting opioid, with a half-life of under one hour and high clearance. Such variability is consistent with the literature, where short-acting anesthetics demonstrate wide inter-patient clearance values, requiring close intraoperative monitoring (Toksvang *et al.*, 2025). The observed differences between individuals reflect the importance of bioanalytical methods capable of providing timely and precise measurements during therapy.

Bioanalysis has shifted in recent years, no longer using the conventional immunoassays, to more sensitive and specific methods. LCMS/MS has become the standard in the quantification of drugs, and it is used in the routine monitoring of the clinic and during drug development (Shi *et al.*, 2021; Verma *et al.*, 2025). Nonetheless, there are new platforms which are fast broadening the horizons of TDM. Near real-time monitoring is now made possible by biosensors and bioelectroanalytical technologies making drug monitoring more accessible and decentralized, beyond the laboratory to point-of-care (Campuzano *et al.*, 2025; Lafi *et al.*, 2023). In the specification of diagnostics and drug monitoring applications, aptasensors, in particular, have proved to be promising (Lafi *et al.*, 2023). Reaching a lower level of invasiveness, enhanced compliance (particularly in children and chronic disease treatment) is being developed by microsampling approaches (e.g., dried blood spots and patient-centered blood-collection), along with improving invasiveness and compliance (Schouwenburg *et al.*, 2022; Oliveira *et al.*, 2023 and Linder, 2019). These

methods resonate with the sustainability and accessibility motifs that have been found in scavenged and microsampling methods reviews on TDM (Schouwenburg *et al.*, 2022). Raman spectroscopy and other new imaging are expanding to pharmaceutical and biomedical applications, and provide a specific non-invasive or minimally invasive monitoring opportunity (Eshbekova *et al.*, 2024). In oncology and autoimmune diseases, integration with pharmacodynamics, pharmacokinetics, and genetic data to inform dosing is becoming a TDM guideline (Li *et al.*, 2024; Toksvang *et al.*, 2025). Psychiatric care reviews also affirm the combination of pharmacogenomics and biomarkers with TDM in delivering personalized treatment, especially where the variance among patients is pronounced (Salatin *et al.*, 2025). Rather than solely relying on bioanalytical measurements, multi-omics, or a combination of genomics and proteomics and metabolomics is now being applied to precision therapeutics and laboratory diagnostics (Ikwelle *et al.*, 2025), and this is congruent with our findings that require layered data to understand outcomes.

As demonstrated in this analysis, pharmacokinetic monitoring can influence medication dosage, but patient outcomes can also be influenced by the circumstances of more general physiological and genetic factors. According to the recent literature, the importance of TDM use in chronic and complex diseases, such as inflammatory bowel disease (Rocha, 2022; Vande Casteele *et al.*, 2021), leukemia (Toksvang *et al.*, 2025), and oncology (Li *et al.*, 2024), is essential. The process of individual care entails a set of pharmacogenetic research, bioanalysis in real-time, and advanced modeling, i.e. in silico simulations, to predict drug reaction (Marques *et al.*, 2024). To establish a channel through which pharmacy and clinical medicine can come together, these facets (aspects) ought to be integrated in day-to-day clinical practice. The greatest weakness of this study is that it considered secondary data. No clinical variables that could be used to influence the results such as severity of the disease, adherence or supportive interventions were present. Furthermore, the pharmacokinetic results were summarized to descriptive means, and more complex tools of modeling like nonlinear mixed-effects modeling that is typically employed in clinical pharmacology were not utilized (Heinig *et al.*, 2020). Moreover, the adverse events could be reported only in a binomial way, and this did not contribute to the close interpretation of the severity and type. This future study should be more oriented to the prospective clinical research, in which more advanced technologies can be used to deconstruct the information and, as well as, to profile the patients. The technologies that will define the future of TDM are Pharmacogenomic data, biosensor-real-time drug concentrations and dose prediction based on artificial intelligence (Zijp *et al.*, 2021; Cao *et al.*, 2025). This will allow tailored and individualized dosing schedules and enhance treatment efficacy. They also require policy and implementation studies that would allow making those innovations available and scaled because the global case studies on the adoption of precision medicine (Qoronfleh *et al.*, 2020) have shown.

5. Conclusion

The present work offers valuable information regarding therapeutic drug monitoring (TDM) as a key interface between pharmacy and clinical medicine in the age of personalized healthcare. The results proved that there was a great variance in the clinical outcomes and pharmacokinetic parameters as the recovery times, treatment efficacy, and remifentanil removal rates exhibited high inter-individual variation. The lack of such consistency highlights that standard dosing regimens cannot be used to guarantee a uniform therapeutic outcome, especially in patients with multi-factorial comorbidities or those with individual metabolic phenotypes. The recent developments in bioanalytical science enhance the capacity of the clinicians and pharmacists to deal with this issue. LC-MS/MS, biosensors, microsampling, and aptamer-based assays in particular are tools that have increased sensitivity, specificity and accessibility of drug monitoring. Together with pharmacogenomics and multi-omics tools, these tools offer a comprehensive platform to not only see the drug concentrations in patients but also the individual biological contexts of patients. This convergence plays an important role in situations when therapeutic windows are small, adverse reactions are common, and failure to treat leaves vital consequences. The clinical implication is obvious: personalized monitoring plans may enhance safety, minimize toxicity, and optimize efficacy in many different therapeutic fields, including anesthesia, and oncology and psychiatry. Besides, the addition of digital health solutions, artificial intelligence, and in silico modeling are sure to further hone the concept of predictive dosing, designing adaptive therapeutic approaches specific to the individual patient. In the future, the future of TDM is to ensure that these technologies are made widely available and scalable across healthcare systems. This will be best achieved through not only scientific invention, but also strong implementation plans, interdisciplinary cooperation, and enabling policy frameworks. In this way, TDM will be a pillar of precision medicine that can be developed, ensuring safer and more effective, patient-centered care.

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