RESEARCH PAPER

Drug Delivery Approaches In Pediatric Anaesthesia: Challenges And Innovations

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ABSTRACT3
Pediatric anaesthesia presents unique pharmacological and clinical challenges due to physiological variability, developmental differences, and psychological factors influencing drug administration.. Conventional drug delivery methods such as intravenous and intramuscular injections are accompanied with pain, anxiety and drug compliance issues in children. It has led to increased application of alternative way of delivery including intranasal, oral, rectal and needle free delivery method with the intention of improving the outcome of therapy with minimal distress. The current paper takes a critical look at these methods of drug delivery in the scope of pediatric anaesthesia, including their pharmacokinetics, clinical applicability, safety, and technological development. To measure efficacy, onset time, bioavailability, and patient acceptability, a literature review and comparative analysis of delivery systems are performed. The findings indicate that the intranasal delivery route is rapid and highly bioaviable, but oral routes are simple to administer with varying absorption. The application of rectal delivery as a method of delivery is beneficial in certain clinical situations despite social and pharmacological constraints. The new technology is needle-free systems, which can revolutionize the practice of pediatric anaesthesia, which is painless and more tolerant. The study concludes that the process of selecting an appropriate delivery system should be customized in respect of the specifics of a patient, clinical requirements and peculiarities of the drug and evolution of new technologies could play a significant role in enhancing the work of pediatric anaesthesia..

Keywords Pediatric anaesthesia, drug delivery systems, intranasal delivery, oral administration, rectal route, needle-free systems, pharmacokinetics, non-invasive techniques..
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INTRODUCTION

Pediatric anaesthesia requires specialized approaches that account for anatomical, physiological, and psychological differences between children and adults. Drugs delivery to children is the most complex activity due to several reasons, such as the fact that organ systems of children are not fully developed, metabolism may be irregular, or they are too sensitive to pharmacological drugs[1]. The traditional use of invasive techniques, such as intravenous injections, is normally associated with procedural anxiety, pain and lack of cooperation, which complicates clinical control.

There has been an emergence of non-invasive and minimally invasive drug delivery methods that are acceptable to enhance patient compliance and therapeutic efficacy. Out of these, intranasal, oral, rectal, and needle-free systems have become the most prominent ones since they have the ability to administer anaesthetic agents effectively with minimum distress[2]. These methods do not only assist in enhancing patient comfort, but also preoperative sedation, analgesia and anxiolysis without invasive interventions.

The increasing demands of patient-centered care in pediatric anaesthesia have driven the study to the maximization of the drug delivery systems that will comply with the safety, efficacy, and acceptability.

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The non-invasive delivery technique techniques have also been extended by pharmaceutical technology like nanocarriers, mucoadhesive formulations and jet injection systems[3]. This paper will analyze the issues surrounding drug delivery in children and evaluate the new ways of drug delivery that can be used to address these limitations.

2. Literature Review

Intranasal drug delivery in pediatrics has been proposed to be a promising but difficult alternative to the conventional administration routes, particularly where intravenous access is difficult or painful in children (Owen, 2026). The author emphasizes that the nasal route is the quickest acting route due to high vascularization of the nasal mucosa and lack of the first pass metabolism that makes this route very suitable in the emergency and perioperative practice. However, Owen cites a host of other problems which limit its clinical application including the intermittency of absorption depending on the state of the mucosa's, the small volumes of dosing and formulation constraints[4]. Pediatric anatomical differences which complicate dosage accuracy and distribution of drugs, I. e. small nasal cavities and erratic clearance rate of the mucous, are also reported by the author. The other important issue that is brought up is patient cooperation that greatly affects the effectiveness of drug delivery. In spite of these, Owen postulates that drug retention and bioavailability are being enhanced by the development of formulation technologies, including mucoadhesive agents and nanoparticle-based carriers. The study also suggests that there should be standardized delivery equipment's which are specifically designed to appeal to children. The regulatory and safety factors are also very important especially in the assurance of non-irritative formulations and uniform therapeutic results. Owen comes up with a conclusion that even though intranasal delivery is a potentially huge potential in pediatric practice, additional clinical trials and technological advancements are required to address existing limitations and provide safe, effective, and child-friendly drug administration systems.

According to Reisner (2025), regional anesthesia has been a paradigm shift in the practice of pediatric surgery that has enhanced the quality of perioperative care and patient outcome to a great extent. According to the author, regional techniques, like nerve blocks and neuraxial anesthesia, provide an opportunity to treat the pain more specifically and use fewer systemic opioids, which leads to fewer side effects of systemic opioids, including respiratory depression and nausea. According to Reysner, the ultrasound-guided procedures have improved the precision and safety of the practice of regional anesthesia allowing visualization of anatomical structures and reducing issues[5]. The other important point the author brings up is that regional anesthesia may help to ensure a faster recovery, shorter hospital stay, and patient satisfaction. These advantages are of particular importance in pediatric groups since they help minimize psychological trauma and ease the postoperative process. However, as Reisner says, there are still some issues, including the fact that a particular training is required, children have anatomical differences, and long-term safety is a problem. The significance of the individualized care in which the anesthetic methods are adjusted according to the age, weight, and clinical condition of a child is also discussed in the article. In addition, Reisner writes about the incorporation of regional anesthesia into multimodal pain management techniques to make it more effective. The author concludes that regional anesthesia is revolutionizing the world of pediatric surgery although research, education, and technological improvement are required to reach the greatest good and the safe and universal use of regional anesthesia.

According to Remi (2023), the contemporary advances in the sphere of pediatric dentistry have been rather successful in terms of pain control and anxiety mitigation in children. The author notes that dental anxiety is one of the greatest hindrances to an effective treatment that may cause avoidance and worsening of oral conditions. In response to this Remi elaborates on the pharmacological and non-pharmacological ways which involve use of local anesthetics, use of sedation techniques and use of behavioural management techniques. The author emphasizes that invasive surgery and child-friendly environments are gaining greater importance in the context of the reduction of fear and discomfort. It has been proved that distraction, cognitive behavioural therapy, and audiovisual aid use are effective methods that are employed to calm down pediatric patients[6]. Also,

Remi notes that there has been an improvement in sedation such as the use of nitrous oxide and oral sedatives which have made the process safer and more compliant with the patient. Another factor considered significant in dealing with anxiety is the parental involvement and communication. Nevertheless, the author observes that there are still some difficulties especially on how to balance between effective pain management and safety issues and the individual differences in reactions to sedation. Another observation made in the article is that continuous learning of dental professionals and application of evidence based practices plays a role in improving performance. Remi concludes that the holistic, patient-centred approach is the most important in the effective management of pain and anxiety in pediatric dentistry and that it involves the integration of medical, psychological, and environmental interventions.

According to McClean (2023), the issue of intranasal drug delivery in pediatric emergency departments attracts increasing attention as a rapid and non-invasive method of administering medicine in an emergency. The author notes that the given course is particularly beneficial in an emergency situation when time is of the essence and the establishment of intravenous access may be difficult. Mazeda, fentanyl and ketamine are some of the drugs that are commonly administered intranasally to sedate, provide analgesia and used in controlling seizures. According to McClean, intranasal delivery is very appropriate in the pediatric context due to its ease of administration and less patient distress[7]. Nevertheless, the author finds various restrictions such as inconsistent absorption of drugs, small volume capacity, and possible nasal irritation. The efficiency of drug delivery also relies on the factors that are related to the device which is used such as the kind of atomizer. McClean emphasizes the importance of training of healthcare providers to give appropriate dosing and form of administration. The article also talks of the current studies that are being conducted to enhance the formulations and delivery systems to increase bioavailability and patient outcome. Nevertheless, McClean finds that the intranasal drug delivery method is a useful tool in the emergency medicine of children, and that it has a great potential to evolve and become a part of the normal clinical usage.

Domingues (2023) asserts that the drug development in pediatrics is not similar to adult pharmacotherapy and this is a special field that is marked with specific needs to ensure safety and efficacy. The author explains that children are not small adults since physiological, metabolic and organ maturity are significant factors that determine pharmacokinetics and pharmacodynamics of the drugs taken. Domingues poses ethical questions in conducting clinical trials on children that most often result in lack of information and use of drugs off label[8]. Formulation issues, including age-appropriate dosage forms, palatable drugs, and flexible dosage schedules are also addressed by the author. Notwithstanding these challenges, Domingues outlines major opportunities that have been brought about by the developments in biotechnology, personalized medicine and novel drug delivery systems. The article reveals that regulation efforts and incentives that may facilitate pediatric research and drug development are important. The collaboration of researchers, clinicians, and regulatory authorities is also referred to as one of the major aspects of the barrier elimination. Domingues makes the conclusion that, although the development of pediatric drugs is still a complicated process, the current innovations, and favourable policies are helping to open the way to safer and more efficient medicine with specific characteristics depending on the needs of a child.

According to Coté (2024), the sphere of practice of pediatric anesthesia is a complicated and professional area of activity that takes into account the specifics of the physiological and psychological state of infants and children. The author stresses that the safe anesthetic practice in pediatric patients requires a proper knowledge of the developmental anatomy, pharmacology and perioperative care. According to Coté, children do not react to anesthetic agents in the same way because of the differences in metabolism, organ activity, and body structure[9]. The significance of cautious dosing, monitoring, and equipment choice is highly stressed to achieve a minimum of risks and patient safety. The other point that the author mentions is the significance of preoperative evaluation, including the evaluation of the medical history, the airway structure, and the risk factors. The intraoperative treatment is directed to the maintenance of hemodynamic stability, adequate ventilation and

adequate pain control. Coté also focuses on the improvement of the sphere of monitoring technologies and anesthetic techniques that has improved the results in the sphere of safety. Another important part of pediatric anesthesia is postoperative care, such as pain control and complications surveillance. The author concludes that the effective and safe administration of anesthesia in the pediatric population should be approached multidisciplinary, with lifelong learning and adherence to evidence-based guidelines.

3. Methodology

3.1 Research Design

The existing research design is the qualitative and comparative research design to provide a systematic evaluation of drug delivery methods in paediatric anaesthesia. The qualitative theory is able to perform a deep analysis of the existing evidence, clinical observations, and pharmacological data as per the non-invasive drug delivery systems. A comparative perspective has been added to assess the differences and similarities between intranasal, oral, rectal, and needle-free modes of delivery. The design is selected in order to have the opportunity to fully understand the performance of both methods in a range of clinical and pharmacokinetic factors[10]. The study is not founded on any primary experimental evidence, but is conducted as a summary of the available scholarly materials such that it generates analytical implications that are related to the practice of anaesthesia in children.

3.2 Data Sources and Search Strategy

Major scientific databases, such as Scopus, PubMed, and Web of Science, are used to conduct a systematic literature search to cover peer-reviewed research in as many ways as possible. The search will cover the period between 2008 and 2025 and this will allow a possibility of searching both the pioneer studies and the current advancements in the drug delivery technologies. It is used to identify the relevant studies through specific keywords and combinations, such as: pediatric anaesthesia, drug delivery systems, intranasal administration, oral sedation, rectal anaesthesia and needle-free injection systems. The search can be narrowed using such Boolean operators as AND and OR to increase the number of articles retrieved[11]. Only published articles in English language with the complete text are included. The first screening of the data is applied in order to remove duplicate records in order to preserve integrity of data.

3.3 Inclusion and Exclusion Criteria

The inclusion criteria are laid down in a manner that the selected studies will have a direct relationship with the research objectives. Articles that use pediatric populations (that is, patients between neonates and adolescents) are included. Studies that cover non-invasive/minimal invasive drug delivery systems during anaesthesia or sedation are of priority. It is believed that both observational studies and clinical trials depict a vast amount of evidence, along with systematic reviews[12]. The studies report the pharmacokinetic parameters, clinical outcomes, safety profiles, or patient acceptability and this will be analysed in detail.

The exclusion criteria are that the population to be studied is a particular one, and that is only an adult population, invasive methods of delivery, intravenous or intramuscular, and articles that lack sufficient methodology or outcome findings. Abstracts of conferences that are not provided in full-text format, non-peer reviewed publications, and studies that are not related to anaesthetic applications are also excluded[13]. This screening process will make sure that the end dataset is narrowed down to a set of results that is trustworthy and consistent with the scope of pediatric anaesthesia.

3.4 Study Selection Process

The study choice is made in a systematic screening. Initially, article retrieved titles and abstracts are examined in an effort to determine potentially relevant studies. During the second step, the full-texts of the chosen articles are considered with regard to the predefined inclusion and exclusion criteria. Only researches meeting the entire requirements are considered in the final analysis. The criteria to be selected are methodological rigor, report result articulateness, and applicability to the primary themes of drug delivery in paediatric anaesthesia[14]. This approach to the study minimizes bias and enhances the precision of the findings.

3.5 Data Extraction and Variables

The data extraction is performed on a standard framework to ensure uniformity of the studies. Some of the most important variables that have been extracted in each of the studies are the

pharmacokinetic parameters (absorption rate, bioavailability, peak plasma concentration and half-life). Clinical outcome measures will be the time of onset of anaesthesia or sedation, its duration and the ability to use it in order to produce the therapeutic effect. The information on safety involves the adverse effects, the complications and the tolerability profiles. The patient acceptability is also determined particularly in relation to level of discomfort, ease of administration and compliance during medication administration. Other variables are the formulation attributes, dosage forms, and technological attributes that are related to every delivery system[15]. The data obtained are grouped into comparative categories which are associated with the four main delivery routes being explored.

3.6 Comparative Evaluation Framework

The systematically analysis of the difference between intranasal, oral, rectal, and needle-free drug delivery systems is created in terms of a comparative evaluation framework. The delivery routes are considered based on predetermined parameters including onset time, bioavailability, duration of activity, safety profile and the patient adherence. The intranasal route is researched as it has high absorption and accessibility of the central nervous system. The oral delivery is measured in regard to convenience and variability in gastrointestinal absorption[16]. The use of rectal delivery is assessed concerning its usefulness in specific clinical situations and constraints. The needle-free systems are considered in regards to technological novelty, pain reduction and potential compliance enhancement.

The comparative framework allows the strengths and weaknesses that follow each method to be noted. It also allows cross-analysis, in order to determine the most suitable delivery systems to be used in some clinical scenarios in pediatric anaesthesia.

3.7 Data Analysis Techniques

The research uses descriptive approaches of analysis to make sense of the data extracted. The quantitative findings of the selected articles are summarized in the form of mean value, ranges, and percentage comparison where applicable[17]. The comparison of cross-studies is done to identify the trends of pharmacokinetic performance and clinical outcomes. The correlation between the delivery routes and the variables such as, onset time, bioavailability and adverse effects are examined qualitatively.

The analysis aims at determining trends which represent relative effectiveness and clinical appropriateness of individual drug delivery systems. The variations in studies are critically evaluated to provide the differences in the sample of patients, formulations of drugs, and type of study. This approach will ensure that results are subtly analysed rather than analysing disjointed information.

3.8 Reliability and Validity Considerations

The article relies on peer-reviewed articles to enhance the credibility, which is found in recognized scientific databases. The data extraction and analysis is done in a uniform manner through the aid of standard criteria and structured evaluation frameworks. Validity has been attained by making use of studies whose methodology is clearly defined and the results of which can be measured. The validity of the results is also supported by the cross-reference of different studies which handled similar variables.

Possible sources of bias such as the publication bias and variations in the study design are considered and addressed by interpreting the results. The types of studies with the variety of clinical trials and systematic reviews contribute to the balanced and comprehensive analysis.

3.9 Ethical Considerations

The study is entirely based on the secondary data sourced in the literature and does not need direct interaction with human beings and collection of primary data. Consequently, there is no need of formal ethical approval. However, the ethical principles are adhered to by providing sufficient coverage of the findings of original research, misinterpretation, and crediting sources[18]. The research follows the principles of academic integrity and research transparency in the study.

3.10 Limitations of Methodology

There are some methodological constraints inherent in the research design. Secondary data may lead to variation due to the difference in studies in terms of population, formulation of drugs, and experimental conditions. It may be a problem of the sample size of non-English publications as it may reduce the scope of the data. Additionally, the meta-analytical statistical tools do not restrict the quantification of the effect sizes across the studies.

Irrespective of such shortcomings, the methodological framework offers a very strong platform on comparative assessment and makes sound observations on drugs delivery practices in pediatric anaesthesia[18]. The systematic and methodological design can be used to make the findings relevant and applicable to the clinical practice.

4. Results and Analysis

4.1 Overview of Comparative Findings

The comparative study of the drug delivery methods in pediatric anaesthesia shows definite differences in pharmacokinetic performance, clinical efficacy, safety, and patient acceptability. Every delivery system possesses their odd strengths and weaknesses grounded on physiological, biochemical and technological factors. Marsal, oral, rectal and needle free systems differ greatly in relation to the time of onset, bioavailability and duration of action and administration[20]. The findings indicate that there exists no general optimal route of delivery, but each of them fits in some clinical situations and conditions of patients. The review is a blend of the findings of different researchers to provide a systematic analysis of these differences.

4.2 Intranasal Drug Delivery Performance

This is the reason why the intranasal drug delivery is considered to be characterized by the constantly rapid action and it is also possible to justify it by the fact that the nasal mucosa has a dense vascular network. The drugs that are taken up this route are directly taken to the systemic circulation and not subjected to hepatic first-pass metabolism. It is a property that enhances bioavailability and quicker therapeutic response, which is quite handy in preoperative sedation and emergency situations. The analysis report indicates that there is a range of 5-15 minutes as the onset time of popular agents such as midazolam and dexmedetomidine.

Intranasal delivery has a relatively high bioavailability, which is usually between 50 and 80 percent, based on the drug formulation and the molecular properties. An added advantage to the clinical efficacy is that certain drugs may go to the central nervous system via the olfactory and the trigeminal pathways. However, the results also indicate the variable absorption in terms of nasal congestion, mucosal inflammation and absence of appropriate administration procedures[21]. Nares irritation and discomfort are mild adverse events that are reported but they do not have a significant impact as regards to patient compliance.

4.3 Oral Drug Delivery Performance

Oral is the most frequently used mode of drug delivery in pediatric anaesthesia since it is non-invasive and quite patient friendly. The results show that oral administration is especially efficient in the routine premedication and anxiolysis[22]. Action is however delayed in comparison with other drugs, and usually takes between 20 and 45 minutes, and therefore may not suit clinical cases where the action is urgent.

Various physiological factors affect the bioavailability of orally administered drugs and these factors are the gastric pH, enzyme degradation, and the liver first-pass metabolism. The comparison shows that there is a high interpatient variability in drug absorption, which results in unstable clinical outcomes. One example is that oral midazolam does not work well when the gastrointestinal conditions are not well, as well as when the patients are of different ages[23]. Despite these disadvantages, oral delivery is still popular in non-emerging setting since it is easy and simplified to administer. The adverse effects tend to be trivial, but problems associated with the taste and difficulties with swallowing are noticed among younger kids.

4.4 Rectal Drug Delivery Performance

The second alternative that may be used during drug delivery is the rectal delivery in situations whereby oral administration or intranasal administration is not possible. As it is revealed in the analysis, rectal delivery provides moderate bioavailability and this tends to be in the range of 30 to 70 percent. Relatively stable pharmacokinetic profiles are due to the partial avoidance of the first-pass metabolism[24]. The time of onset of rectal administration is medium, ranging between 15 and 30 minutes and so it can be used in some clinical situations where rapidity is not important.

The findings indicate that the rectal administration is particularly useful with patients who are uncooperative or where there is nausea and vomiting. However, the absorption of drugs which are influenced by factors such as rectal contents and blood flow through mucous is still very variable. Social and cultural factors also affect the acceptance of this route

by the patient and the caregiver. Such practical and psychological obstacles have rendered rectal **4.5 Needle-Free Drug Delivery Performance**

The needle-free drug delivery system is a major innovation in anaesthesia in children. This is attributed to the fact that these systems are based on high pressure methods of drugs delivery, such as jet injectors, to deliver drugs into the skin without using needles. It was established that needle-free systems are rapid in drug absorption and their onset duration compares to intramuscular injections, which have a onset time of 5-10 minutes.

Needle-free delivery has a high bioavailability (80-100 percent) (depending on the drug formulation and the device) and is considered a safe method of drug delivery. The pain and anxiety caused by needles is eliminated, which is one of the factors that lead to an enhanced patient compliance and satisfaction[25]. Also, these systems minimize the risks of needle-stick injuries and cross-contamination and increase the overall safety of clinical settings.

Despite these advantages, the analysis also creates certain limitations including high start-up expenses, maintenance, and trained employees[26]. Drug dispersion and penetration depth can also be variable and can consequently influence delivery consistency. Nevertheless, the pediatric anaesthesia has high potential of greater application with the use of needle-free systems since technological advances continue to address these concerns.

.6 Comparative Numerical Analysis

Table 4.1: Comparative Numerical Evaluation of Drug Delivery Systems in Pediatric Anaesthesia

S. No.	Delivery System	Onset Time (min)	Bioavailability (%)	Duration of Action (min)	Safety Level (1–5)	Patient Acceptability (1–5)
1	Intranasal	5–15	50–80	30–90	4	4
2	Oral	20–45	30–60	60–120	4	5
3	Rectal	15–30	30–70	60–120	3	3
4	Needle-Free	5–10	70–90	45–120	5	5

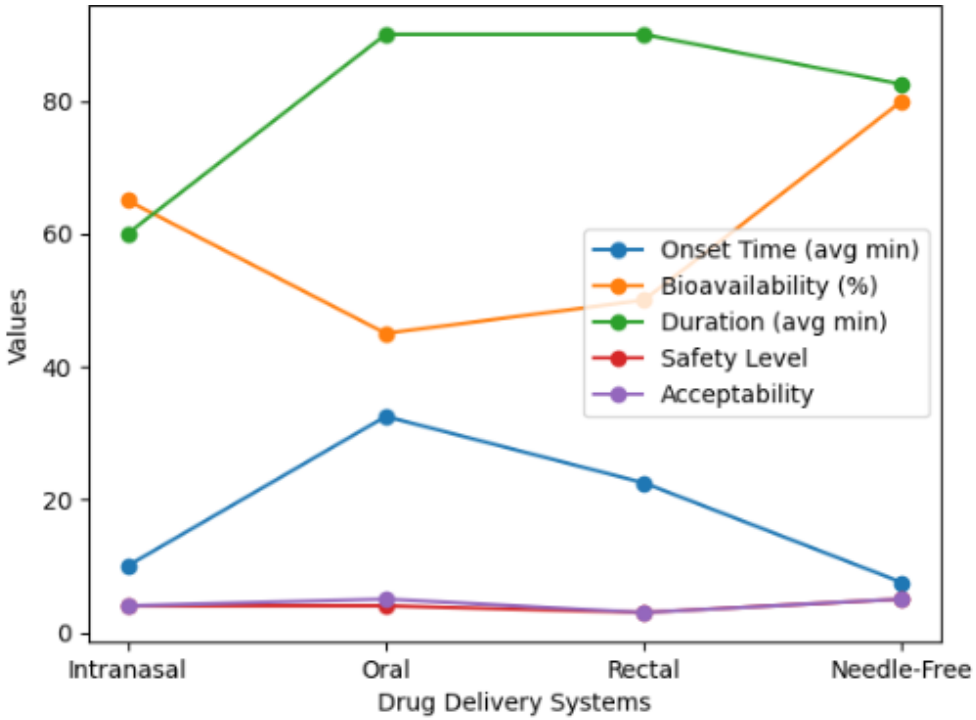

Figure: Comparative Numerical Evaluation of Drug Delivery Systems in Pediatric Anaesthesia

The statistical data indicates that intranasal and needle-free systems have shortest onset time and can thus be used in a fast-sedation procedure. Needle free systems have the highest bioavailability and safety rating and this is indicative of their technological advantage[27]. The oral mode is also the most acceptable by the patient, since it is non-invasive compared to the rectal mode which is less acceptable with an average pharmacokinetic profile.

4.7 Trend Analysis and Interpretation

According to the trend analysis, the trend is towards the utilisation of non-invasive and patient-friendly modalities of drug delivery in the pediatric anaesthesia. Needle-free and intranasal systems are becoming more popular because of their fast acting and better compliance. Oral administration remains the most widespread in a normal clinical practice with rectal administration being an exception.

It is also discovered that technological innovation is a significant aspect that influences efficiency of drug delivery [28]. There is also improved nasal and oral systems, which are developed through the science of formulation like mucoadhesive agents and nano-carriers. Similarly, the developments in the engineering of the devices are making needle-free technologies more functional.

4.8 Synthesis of Findings

The analysis of the results suggests the importance of personal selection of drug delivery systems in terms of context. Intranasal mode of administration is the ideal mode of administration in speed of sedation, oral mode of administration is the most prevalent mode of administration, rectal mode of administration is another mode of administration under some limited circumstances and needle-free systems are the future of administration. Integration of pharmacokinetic and clinical outcome is a scientific method of decision making in pediatric anesthesia[29].

The argument proves the fact that the evolution of drug delivery technologies is changing the practice of pediatric anaesthesia by concentrating on the safety, efficacy, and comfort of patients. These approaches and their current shortcomings are most probably to be refined further and improved with further research and innovation.

5. Discussion

The findings stress the importance of adopting the appropriate drug delivery system according to the clinical requirements and patient characteristics. Intranasal delivery is an excellent solution to a quick renal analgesia and sedation, especially in the preoperative care. This has enhanced the clinical

utility since it can circumvent the hepatic metabolism and generate direct central nervous system effects.

Oral delivery is still used as a method of routine procedure because it is simple and does not involve invasiveness[30]. However, its limitations demand keen consideration of dosage and time so that they may be applied to achieve intended therapeutic outcomes. Oral drug delivery among children can be improved by the development of new formulation technologies such as taste-masking and controlled-release technology.

Rectal administration is still a viable choice in specific clinical conditions. It can be used particularly in non-cooperative patients or patients with destroyed oral or nasal tracts. There is a need to conduct more research on the issue of variability of absorption and patient acceptability.

Another significant advancement in the field of drug administration in children is with regard to needle-free systems[31]. The technologies comply with the reduction of pain and anxiety and the maintenance of the therapeutic efficacy. The additional design of devices and formula of the drugs are likely to make their needless methods more viable and accessible.

6. Conclusion

Pediatric anaesthesia has the requirement that the drug delivery systems are safe, effective and comfortable to the patient. All the intranasal, oral, rectal, and needle-free delivery methods have their advantages and disadvantages. Intranasal delivery offers quick and effective absorption of drugs whereas oral intake makes the administration easy. The second option of rectal delivery is in special situations, and the new technology of needle-free systems is capable of transforming the landscape of anaesthetic care in children.

The use of very advanced pharmaceutical technologies and patient-focused methods should be included in optimization of drug delivery in children. The research on how to improve bioavailability, reduce variability, and make all delivery systems more acceptable to the patients should be conducted in the future. The progress of new formulations and devices of drug delivery will be instrumental in the enhancement of the discipline of pediatric anaesthesia

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