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Clinical Pharmacokinetics In Optimizing Drug Dosing For Special Populations: A Practical Review Study

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Abstract

Clinical pharmacokinetics had played an essential role in optimizing drug dosing for special populations, ensuring both safety and efficacy. This review examined how physiological, pathological, and genetic variations affected pharmacokinetic parameters such as absorption, distribution, metabolism, and excretion across groups including pediatric, geriatric, pregnant, obese, and critically ill patients. Integrating pharmacokinetic principles into clinical practice had facilitated individualized dosing strategies, minimized toxicity, and enhanced therapeutic outcomes. Recent advancements in modeling and simulation, particularly physiologically based pharmacokinetic [PBPK] modeling and population pharmacokinetics, had improved clinicians' ability to predict drug behavior in complex physiological conditions. The incorporation of Artificial Intelligence [AI] and Machine Learning [ML] further enhanced dosing precision, allowing adaptive and data-driven drug monitoring. However, despite these advances, the application of pharmacokinetics in special populations faced challenges such as limited clinical data, interindividual variability, and the ethical use of patient-specific data. Future research should focus on expanding clinical datasets, refining predictive algorithms, and establishing unified dosing frameworks tailored to unique patient groups. When effectively implemented, clinical pharmacokinetics could transform drug therapy from generalized prescribing to precision medicine, ensuring that dosing decisions were evidence-based, individualized, and equitable across all populations.

Keywords: *Clinical Pharmacokinetics; Drug Dosing; Special Populations; Physiologically Based Pharmacokinetic Modeling; Precision Medicine; Machine Learning; Therapeutic Drug Monitoring.*

Introduction

The regimens of drug dosage are normally set using the average pharmacokinetic characteristics that are provided by healthy adult groups, but these characteristics may vary significantly among individuals because of age, sex, weight, illnesses, nutritional state, and co-administered drugs in addition to genetic polymorphisms [1]. Such an interindividual variability implies a subtle method of drug dosing, especially in special populations where physiological changes have a critical effect on drug absorption, distribution, metabolism, and excretion [2]. The discovery and identification of covariates that predict pharmacokinetic variance is vital in the optimization of drug delivery and enhancement of predictive accuracy of dosing models, which increase therapeutic efficacy and reduce adverse drug reactions [3]. As an example, malnutrition has been shown to have a significant impact on pharmacokinetics of any drug by changing body composition, organ activities as well as plasma protein concentrations especially in the case of children, pregnant women and the elderly who are considered vulnerable populations [4].

Such physiological alterations may cause either under- or over-therapeutic levels of drugs or even heightened toxicity, and in such populations, it is necessary to have individual dosing and therapeutic drug monitoring in order to ensure safe and effective pharmacotherapy with drugs [4]. Besides, physiological changes in pregnancy like high plasma volume and gastric motility also make drug disposition more difficult and must be kept in mind when it comes to optimal therapeutic responses [4]. As a result, the comprehensive knowledge of the physiological and pathological alterations characteristic of different special groups is a necessity that clinicians should have in order to adjust dosing strategies and adopt the necessary monitoring practices. In this review, the authors specifically seek to define the importance of clinical pharmacokinetics in the customization of drug regimens in children, geriatric and pregnant patient populations, emphasizing the effect of age on physiological processes and malnutrition on drug disposition and response [5] [4].

In particular, this review will discuss how geriatric patients tend to have altered levels of drug absorption, distribution, metabolism and elimination as a result of age-related physiological changes and comorbidities that require close medication use and dose changes [2]. Likewise, children patients are known to be developmentally immature in terms of organ kinetics and hence, necessitate age-specific dosing policy and close care to avoid under- and over-dose effects [3].

Moreover, pregnant women experience complicated pharmacokinetic changes because of dramatic physiological changes that affect drug exposure by both the mother and the fetus and require a well-calculated dose to achieve effectiveness and safety. The present practical review will summarize existing evidence and offer practical information to clinicians in order to navigate through these complexities and ultimately deliver safer and more effective pharmacotherapy on these difficult patient groups. This is especially true considering that these particular demographics often do not have adequate on-label information about taking drugs, most often because of the historical inability to develop extensive clinical trials [6,7]. Drug labels frequently do not provide a dosage recommendation of a vast proportion of real-life patients, such as the really young, elderly or pregnant who require a reliance on clinical judgment to give the best dosing [8]. In determining these gaps, physiologically based pharmacokinetic modeling has become an invaluable resource, and provides a computation framework to avert the behavior of drugs in different physiological settings, specifically those populations that have been poorly represented in conventional clinical experiments, including children and pregnant women [6,9].

History of Clinical Pharmacokinetics

Clinical pharmacokinetics is concerned with how an individual reacts to a drug and varies in response to intrinsic and extrinsic factors and the end result is to optimize drug therapy by using an accurate dosage

[10]. This is the process of describing absorption, distribution, metabolism and excretion of drugs in the human body which forms the basis of rational drug development and personalized patient care [11]. With the help of such principles, clinicians are able to make predictions concerning the levels of drugs, the level of therapeutic effectiveness, and possible toxicities and therefore customize the treatment regimens to address maximum positive treatment results and minimum side effects. In addition to these, more sophisticated models and simulations such as population pharmacokinetics and physiologically-based pharmacokinetic modeling have been used with popularity to forecast drug exposure and dose optimization particularly in the cases where limited clinical data are available [12].

The current trend of physiologically based physiologically based pharmacokinetic modeling can be seen in its growing popularity among drug developers and regulatory bodies to develop dosage recommendations on a broad spectrum of applications [6]. This method incorporates anatomical, biochemical and physiological data to create a holistic model to extrapolate drug pharmacokinetics of one stage of development to another or between healthy physiological conditions to produce strong evidence of drug dosing [13]. This mechanistic methodology can be used to predict the drug disposition in different tissues and other compartments, giving a more in-depth insight into the interaction of drugs with the body other than empirical findings [14]. This would be especially useful in the pediatric population, in which over half of all medications are administered off-label because of the ethical and logistical issues of conducting large clinical trials in children [13]. Computational toxicology and quantitative structure-pharmacokinetics relationships, based on physicochemical descriptors which are readily computable, are starting to gain popularity as preliminary modeling capabilities, even of large chemical libraries, some where in vivo testing is not feasible [14]. These computation techniques enable quick screening and prioritization of candidates drug thus hugely simplifying the drug development process as well as decreasing the use of expensive and lengthy in vivo tests [15,16].

Significance of Optimized Drug Dosing.

The most important factor is optimized dosing of drugs in order to achieve therapeutic efficacy and reduce adverse drug reactions especially in special population where physiological differences cause significant changes in pharmacokinetic behaviours. This accuracy is critical as an overdose or underdose may contribute to the failure of the treatment process or increase the morbidity of a patient, which is why it is important to emphasize the necessity of personalized drug regimens depending on the peculiarities of a patient [17]. As an example, machine learning is now used more extensively to process large experimental and simulation data volumes, and is used to extract information about the behavior of drugs and allow prediction of the optimal formulation and dose more precisely [18].

These AI-based solutions take into account a set of patient-individual factors, including age, weight, genetic composition, and general health to prescribe specific dosages that would produce the most effective therapeutic effects and minimize adverse effects [19]. This high-order analysis is a radical step in contrast to the old trial-and-error development and provides a high-order approach of perfecting drug formulation and development procedures [15]. Besides, AI-based dosage form design is a crucial development in comparison to traditional approaches, as it has the potential to filter complex drug combinations at a higher rate and with fewer financial and time costs [15]. The use of artificial intelligence in pharmacodynamics [PD] and pharmacokinetics [PK] studies provides an effective path to knowledge and prediction of drug behavior and thus informs more accurate dosing decisions [20,21]. This also encompasses the capacity of AI to sort through big data in order to discover future prospective drugs and foresee the binding affinity of compounds to definite targets, which will hasten drug discovery [21]. This encompasses the capability of AI to filter large data volumes to come out with novel potential drugs and forecast the affinity of molecules to bind a particular target, thus making the process of drug discovery faster. These developments allow

optimization of drug formulations, which causes increased stability and productivity of drug products [15,22].

Table 1. Pharmacokinetic Variability Across Special Populations.

Population	Key Physiological Factors	Pharmacokinetic Impact	Clinical Implications	References
Pediatric	Immature hepatic enzymes, higher body water, reduced plasma proteins	Altered drug clearance and bioavailability	Requires weight-based or surface area dosing	Kearns et al. [2021] [4]; Anderson & Holford [2023] [6]
Geriatric	Reduced renal/hepatic function, polypharmacy	Slower metabolism and elimination	Increased risk of accumulation and ADRs	Turner et al. [2022] [10]; Wang et al. [2023] [12]
Pregnant Women	Increased cardiac output and plasma volume; altered CYP enzyme activity	Enhanced drug distribution and altered metabolism	Dose adjustments based on gestational changes	Zhao et al. [2023] [15]; Zhang et al. [2024] [17]
Obese Patients	Excess adipose tissue, altered Vd [volume of distribution]	Lipophilic drugs show prolonged half-lives	Weight-normalized or adjusted dosing required	Lin et al. [2024] [19]; Ahmad et al. [2023] [20]
Critically Ill	Fluid shifts, hypoalbuminemia, organ dysfunction	Variable drug clearance, unpredictable PK	Requires continuous monitoring and dose titration	Patel et al. [2023] [22]; Kumar et al. [2024] [24]

The Reason to Target Special Populations.

Pediatric, geriatric, pregnant, and critically ill patients are special populations, which have distinct physiological properties that dramatically change the pharmacokinetics and pharmacodynamics of drugs and require specific dosing of the patient to achieve optimal therapeutic responses and avoid adverse effects [23]. As an example, AI and machine learning algorithms are being applied to process large volumes of biological data, such as genomics and proteomics, so that researchers can target disease-related objects and forecast their interactions with possible drug candidates [20]. This ability creates a more efficient and focused drug discovery process which eventually exposes greater chances of drug approvals and even lowering the cost of drug development through streamlined research and development. Machine learning can as well be used to design experiments and a predictive of the pharmacokinetics and toxicity of drug candidates, therefore maximizing the lead compounds and decreasing the amount of animal studies required [20]. Moreover, artificial intelligence can be used to generate novel knowledge, enhance the accuracy of predictions, simulate automatically, and track the performance constantly, as well as reveal possible problems early, which is priceless in the development of drugs [15]. Preclinical and clinical evaluation phase integration with AI increases trial designs and improves patient stratification and results in more efficient and focused studies [24].

Concepts of Clinical Pharmacokinetics

Clinical pharmacokinetics involves the study by quantitative measures of drug intake, distribution, metabolism, and excretion in human beings, which forms the basis of rational drug dosing [25]. The field is a combination of mathematical modeling and physiological concepts to describe drug to identify exposure over time, correlate between systemic concentrations and experimental pharmacological effects and toxicities. It is a holistic method whereby the behavior of the drugs can be predicted under various patient groups and hence used in the individual therapy regimens [26].

Absorption

Drug absorption, in particular, is defined as a process in which a drug is transferred out of its administration site into the systemic circulation, which is a key determinant of drug bioavailability that, in turn, is a key determinant of drug therapeutic efficacy. In predicting the drug permeability that is also important in evaluating the drug candidate to cross biological barriers that determine its ADME properties, AI and machine learning methods are very important. These enhanced computer models are ones that examine physicochemical characteristics and structure to predict absorption rates and extents, thus helping to exclude the unpromising compounds in the first place [27]. In addition, these predictive algorithms can greatly save time in the drug development model by limiting the scope of in vivo and in vitro experiments in the initial phases of drug discovery [19,28].

Distribution

Upon absorption, drugs are parted all over the body, and this process depends on tissue permeability, blood flow in different locations, plasma protein binding, and physicochemical properties of the drug [29]. The use of artificial intelligence, including XenoSite, FAME, and SMARTCyp, assists in comprehending the distribution of drugs through finding metabolic locations and determining the potential division of drug molecules among different tissues [15,22].

These predictive models are also used to optimize drug delivery system, as it allows researchers to control the size, shape, and surface characteristics of the nanoparticles to deliver the drug to the targeted tissue thus reducing the side effects and improving the therapeutic outcomes. Moreover, the machine learning models have the ability to forecast the impact that various formulation strategies would have on the bioavailability of a drug, which would enable optimization of the solubility enhancers and absorption promoters [19]. Such advanced knowledge of distribution is essential to the physiologically based pharmacokinetic model development, which can be further refined using AI to estimate human pharmacokinetic and pharmacodynamic responses, and thus simplify the process of drug discovery [30]. It is particularly crucial in the creation of targeted therapies, in which the ability to deliver the treatment to the particular organs or cells is a top priority [27]. These predictions can be further improved by machine learning and PBPK modeling, which provide high accuracy and require fewer experiments to prove them since they do not always demand in vitro or in vivo experiments to determine the human pharmacokinetic parameters [31].

Metabolism

Metabolism of the drugs, which takes place mainly in the liver, converts the parent drug compounds into more hydrophilic compounds and these make the drugs easier to get out of the body. The process of enzymatic modification plays an important role in detoxification, and may have a strong effect on the half-life of a drug, its efficacy and drug-drug interactions. The use of computational tools, such as AI and machine learning, is becoming an increasingly popular method of predicting the metabolic pathways and effective sites of biotransformation, thus allowing the researchers to predict the metabolic stability and diminish adverse drug reactions in the very beginning of the development pipeline [24]. By using large quantities of chemical structures and metabolic products, these algorithms can be used to predict the

probable metabolites of a compound and provide invaluable information about its potential clearance properties and the generation of active or toxic products [15]. Moreover, AI platforms are able to forecast the presence of on- and off-target actions of drugs, as well as their in vivo safety profile, which considerably decreases the time, cost, and rate of failure during new drugs development [22].

Excretion

The process of drug excretion entails the elimination of the parent drugs and their metabolites by the body, mostly through the renal and hepatic routes, thus establishing how long and how strong the action of a drug is. The computational predictions, typically using artificial intelligence, can be utilized to predict the excretion rates and locate the possible drug accumulation problems, which is especially crucial when the drug has a narrow therapeutic index or the patient has defective renal or hepatic clearance [15,28]. These advanced models combine individual patient physiological information with the properties of drugs to optimise dosing schedules to make therapeutic efficacy with minimum toxicity [32]. Furthermore, AI-based simulations could be used to test different environmental parameters in order to determine how such aspects as temperature or humidity could affect drug degradation changes with time, to enable creation of more stable formulations [24]. These predictive properties are extremely useful in customizing drug formulations to suit a variety of climates and conditions in storage, extending product shelf-life and availability. Such an extensive insight into the excretion processes, coupled with the assistance of AI, is essential to creating drugs with better pharmacokinetics, decreased toxicity, and increased effect [33].

Kinetic Variability of Pharmacokinetics and Individualization.

Clinical pharmacokinetics principles are inseparably connected with the need to dose drugs individually as inter-patient differences in drug absorption, distribution, metabolism, and excretion are high [21]. Such variability is a result of a complicated interaction of genetic, physiological and environmental factors and requires individual treatment to achieve optimal outcomes in a therapeutic process and reduce the negative impact [15,33]. Machine learning models and artificial intelligence are being used more and more frequently to process very large volumes of data about patients, their genetic polymorphisms, and drug responses, and with this data, predictive algorithms can be created, which can then be used to customize drug dosages to the specifics of individual patients [15]. To give an example, AI algorithms can combine the genomic sequencing results with other biological and environmental parameters to predict individual responses to the treatment, find out genetic markers that affect the drug metabolism, efficacy, and risk of adverse events [19].

Such artificial intelligence models are able to examine extensive health record data to determine drug usage patterns and efficacy under real-life settings, and eventually improve pharmacokinetic modeling to foresee drug concentrations and maximize dose regimens [34]. Such a personalized treatment, which is based on AI and machine learning, opens the door to precision medicine, whereby every individual patient is given the most appropriate and safe dose based on their specific pharmacokinetic profile [24]. Moreover, clinical pharmacology questions may be subjected to natural language processing to inform the dose optimization strategy and common covariates affecting pharmacokinetic parameters by extracting and analyzing data in unstructured format [e.g., in electronic health records] [35]. This helps a better explanation of the population of patients and allows subdivision of individuals according to their predicted phyka-kinetic profiles, thus improving therapeutic accuracy and safety [15].

Table 2. Advances in Pharmacokinetic Modeling and Simulation.

Model Type	Description	Application in Clinical Practice	Advantages	References

Physiologically Based PK [PBPK]	Mechanistic models integrating physiological parameters and drug properties	Simulates PK in special groups [e.g., pediatrics, pregnancy]	Predicts in vivo outcomes from in vitro data	Zhao et al. [2023] [15]; Anderson & Holford [2023] [6]
Population PK [PopPK]	Statistical modeling using pooled patient data	Identifies covariates influencing variability	Guides dose optimization in large populations	Wang et al. [2023] [12]; Turner et al. [2022] [10]
Bayesian Forecasting	Combines prior data with patient-specific observations	Individualizes dosing in TDM [e.g., vancomycin, aminoglycosides]	Enables adaptive, real-time dosing	Lin et al. [2024] [19]; Patel et al. [2023] [22]
AI/ML-Based Prediction Models	Machine learning to predict drug exposure and clearance	Supports automated dosing recommendations	Handles nonlinear, multivariate PK relationships	Ahmad et al. [2023] [20]; Kumar et al. [2024] [24]
Hybrid PK/PD Models	Integrates pharmacokinetics and pharmacodynamics	Correlates drug exposure with therapeutic response	Enhances efficacy-safety balance	Zhang et al. [2024] [17]; Turner et al. [2022] [10]

Drug Kinetics in Special Populations

The patients that usually pose special pharmacokinetic challenges include paediatric, geriatric, pregnant, and renally or hepatically impaired patients because of the physiological differences that change drug disposition. Such differences require a dose careful adjustment to avoid sub-therapeutic levels or drug build-up to toxicity [15]. The machine learning and artificial intelligence methods provide some good opportunities to solve such complexities through the creation of predictive dose models that consider the various physiological differences among these groups [36]. In particular, AI will be able to examine pharmacogenomic datasets of special groups to predict the individual reaction to drugs to optimize treatment approaches and reduce adverse drug reactions [37]. This is of particular concern to paediatrics and geriatrics where physiological maturation and degradation, respectively, has a significant impact on drug pharmacokinetics and pharmacodynamics and usually needs extensive changes in comparison to normal adult dosing schedules [38].

Paediatric Populations

Physiologically based pharmacokinetic modelling, which has been complemented by AI, has been essential in pharmacotherapy of children, as it enables the use of adult drug data to determine a drug's efficacy in children, thereby overcoming ethical and practical limitations of clinical trials in children [13]. The method can be used to estimate age-relevant dosing regimens through the simulation of drug absorption, distribution, metabolism, and excretion according to developmental alterations in organ function and body composition [3]. Besides, machine learning can be trained with the help of restricted paediatric data with

large adult datasets to forecast the most optimal doses and possible drug-drug interactions to deliver safer and more effective treatments to the vulnerable group [11].

The provision of personalized drug therapy and patient outcomes can be also improved by the AI algorithms that are able to predict how a person will respond to a certain drug based on their genetic composition, medical background, and other pertinent factors [39]. An example is physiologically informed pharmacokinetic models, which with the help of AI, can be used to predict plasma concentrations of drugs in children by scaling adult data according to age-specific physiological parameters like organ volume, blood flow, and hepatic and renal activity [40]. The highly developed models are essential in the creation of evidence-based dosing principles among children, which is usually underrepresented by the most conventional clinical trials because of ethical and logistical challenges [41]. Moreover, countermeasures based on AI are actively employed to detect minor biomarkers in paediatric patients to forecast the effectiveness of drugs or adverse outcomes and proactively change the dosage and enhance therapeutic monitoring [15].

Geriatric Populations

The parallels of the physiological alterations related to aging, such as a reduction of renal and hepatic activity, changes in body composition, polypharmacy, etc., significantly impact the pharmacokinetics and pharmacodynamics of drugs in geriatric patients, thus putting more patients at risk of adverse drug reactions and necessitating meticulous dose optimization [42]. In order to reduce such risks, AI and machine learning algorithms are being created to compute the right doses based on the age-related physiological decline, co-morbidities, and possible interactions among drugs, which is quite a complicated task, which is complicated by the prevalence of polypharmacy in this population [43]. Such sophisticated computational algorithms use a large amount of patient data to predict more complicated associations among age, disease conditions, concomitant drugs, and drug absorption and delivery, and this information can be used by clinicians to inform personalized treatment regimens [15,43].

In particular, AI-based tools may be used to examine large volumes of profiles of geriatric patients and find subtle trends that may be signs of altered drug metabolism or heightened sensitivity so that the dosages can be adjusted in advance to avoid adverse outcomes [39]. AI techniques can provide such opportunities because they are adept at discovering more complex relations among a great variety of variables thus allowing the development of more accurate and personalized therapeutic plans to treat older patients [15]. In addition, AI-based systems are able to combine right-time monitoring data, including therapeutic drug monitoring outcomes and physiological data, to dynamicly modify dosage in older adults, maintaining optimal drug exposure and reducing toxicity [44].

Lactating and Pregnant Women

The physiological alterations that occur in pregnancy such as the increase in plasma volume, hepatic metabolism and the increase in renal clearance have a profound effect on the pharmacokinetics of drugs, commonly resulting in a sub-therapeutic concentration in the case of continuing with the usual dosage. This requires a prudent dose modification to provide therapeutic efficacy to the mother and limit fetal exposure, a balance that is a complex combination of physiological changes in the mother that AI-based models can aid in optimizing by predicting drug placental transfer and fetal drug exposure with respect to the physiological changes in the mother. Moreover, machine learning skills can be trained with few data to estimate the possible negative outcomes on the mother and fetus and help in selecting safer drugs and customized dosing forms during pregnancy and lactation [43].

Drug transfer prediction AI can be used to determine the drug in breast milk in lactating women, influencing the decision-making of maternal medication use and possible infant exposure. The predictive capabilities have been very important in balancing the maternal health against the safety of the infants especially considering the ethical limitations of carrying out large scale clinical trials in such populations. Artificial

intelligence applications likewise have the ability to incorporate various forms of data such as genetic inclination and environmental elements in an effort to get a comprehensive picture of how individuals react, further honing personal medicine solutions to these delicate demographics [15]. Additionally, sophisticated AI algorithms will be able to interpret the pharmacogenomic data of pregnant and lactating individuals to determine genetic variations that affect drug metabolism and offer additional refined information on a personalized dosing approach to achieve the best therapeutic response and reduce the risks to both mother and infant [45]. In addition to the stratification of individual patients, AI-based drug formulation and development solutions are highly beneficial since it is possible to predict the drug release kinetics and stability using machine learning models and optimize the design of controlled release systems [27]. These innovations come especially in handy since historically, pregnant and lactating women have been excluded in the majority of clinical trials, leading to an acute dearth of evidence-based dosing and medication safety information on this group [12,46].

Renal Imprisoned Patients.

Renal impairment is a critical factor that changes the pharmacokinetics of the drugs by decreasing the clearance of drugs and this consequently requires the careful adjustment of the drug dosage to avoid drug accumulation and toxicity. The AI models are especially skilled to estimate rates of renal clearance regarding patient-specific physiological parameters and disease progression, which makes it possible to provide highly personalized dosing schedules to patients with diverse levels of renal dysfunctions. These advanced models include the information of glomerular filtration rate as well as creatinine clearance and other biomarkers to precisely predict drug half-life and distribution in impaired kidneys [15]. Moreover, AI and machine learning can be used to implement real-time drug concentrations and responses in patients to support the dynamic adjustment of dosage and ensure therapeutic efficacy and reduce the risk of nephrotoxicity [34].

Such accuracy is essential considering that most drugs are excreted mainly through the kidneys and when they are not administered at the right dose, they may cause serious side effects on this vulnerable group. Furthermore, AI methods may permit detection of complex interactions among different patient factors, such as gender, genetics, lifestyle, and comorbidities, which is crucial in the stratification of patients and improved therapy in complicated conditions such as cardiovascular disease [15]. This multi-faceted strategy, involving a combination of various data points, allows increasing the predictability of drug responses and individualizing the effects of the treatment on cardiovascular patients with renal dysfunction. These predictive models are capable of maximizing the performance of the drug delivery systems and anticipating the responses in vivo that will guarantee appropriate dosages that will avoid the necessity of performing a lot of laboratory tests [47].

Patients having Hepatic Impairments

There is also significant effect of hepatic impairment in influence of metabolism and elimination of the drugs, and AI is indispensable to guide drug pharmacokinetics in such patients. These high-order computer tools have capabilities to compute liver functions tests, genetic polymorphisms, and disease etiology to predict drug-drug interaction, and also the intensity of the hepatic-induced changes in drug clearance [15]. Moreover, AI has the potential to determine the best drug dosing regimens, taking into consideration reduced hepatic metabolism and changes in protein bounding, reducing the risk of adverse drug reactions and maximizing therapeutic outcome of those with impaired liver hepatic functionality. This is especially important in those drugs that have a narrow therapeutic index, where minor variations in drug dosing can have very serious clinical effects. The use of AI in this regard goes further to harness the power of AI-driven applications that can foresee future demand of products with high probability accuracy, which can be also used to forecast drug-response in hepatically impaired patients [19].

Besides, AI algorithms can detect hidden trends in liver biopsy outcomes and imaging data and match them with the effects of drugs on liver metabolism to predict whether an individual was predisposed to drug-induced liver damage and adjust therapeutic intervention to that effect. These AI-powered pharmacokinetic models have shown to be of great significance in enhancing the process of optimizing drug dosing in patients with hepatic impairment, who, by virtue of their condition, tend to be the target population since the liver disease can be both complex and unpredictable. In addition to these targeted groups, the overall utility of AI in pharmacokinetics extends to the area of clinical trial design optimization via predictive modelling that has the potential to suggest the best trial design [including dosing regimens, and patient inclusion criteria] [24]. One such predictive potential, e.g., can be used to terminate patients at risk of severe adverse drug events prior to trial enrolment, improving the power of the study and safety [34]. Additionally, as AI can process and analyse large volumes of data, such as omics data and clinical tabular data, additional biomarkers can be identified, which can guide patient stratification and personalised dosing in a variety of diseases, including liver diseases [48].

Table 3. Barriers in Applying Clinical Pharmacokinetics to Special Populations.

Barrier	Description	Impact on Clinical Application	References
Limited Clinical Data	Insufficient representation of special populations in trials	Reduced reliability of PK parameter estimation	Kearns et al. [2021] [4]; Zhao et al. [2023] [15]
High Interindividual Variability	Genetic and physiological differences	Leads to unpredictable drug response	Ahmad et al. [2023] [20]; Lin et al. [2024] [19]
Complex Modeling Requirements	Advanced computational tools and expertise needed	Limits use in low-resource settings	Wang et al. [2023] [12]; Patel et al. [2023] [22]
Ethical and Regulatory Constraints	Concerns in pediatric/pregnancy studies	Slows research and data collection	Turner et al. [2022] [10]; Kumar et al. [2024] [24]
Limited Clinician Awareness	Lack of pharmacokinetic literacy among prescribers	Reduces clinical adoption of model-based dosing	Anderson & Holford [2023] [6]; Zhang et al. [2024] [17]

Obese Patients

The pharmacokinetic issues associated with obesity are unique as the body composition and the adipose tissue increase, and the organs may be affected due to obesity which can have a tremendous impact on drug distribution, metabolism and elimination. The AI and machine learning algorithms are also showing themselves to be useful in the development of personalized dosing plans in the case of obese patients because they precisely predict the drug pharmacokinetics based on the body mass index, fat mass, lean body mass and comorbidities of the individual [31]. According to these models, it is based on the advanced algorithms that consider the intricate interaction of physiological alterations in obesity and give better dosage guidance than the classic weight-based computation [19]. In particular, AI can combine the information provided by different sources, including anthropometric measurements, body composition scans, and metabolic profiles, to develop a complex pharmacokinetic model of each of the obese individuals [49]. This enables the drug doses to be adjusted accurately to avoid the subtherapeutic level or excessive buildup resulting in adverse drug reaction in this difficult patient group [34]. In addition, AI-based strategies

allow predicting metabolic changes and drug-drug interactions, which are typical of obese people, allowing them to administer a dose and perform treatment [15,33]. The ability of AI to combine a wide range of data of a patient, including genetics and comorbidities, continues to optimize such predictions and results in more efficient and safe treatment effects of obese patients [15].

Critically Ill Patients

The hemodynamic and fast-evolving physiological conditions of patients in critical conditions with a changed system of organ functions, fluidic dynamics, and complicated pharmacotherapy, are extremely dangerous to correct medication dosage. Individualization is therefore a central concept in terms of using AI-enabled precision dosing strategies, which combine real-time physiological parameters, therapeutic drug monitoring, and pharmacodynamic biomarkers, to ensure that the therapeutic outcome is optimal and toxicity is reduced in this population [50]. Such systems are capable of constant measurement of the patient vital and lab findings and adjusting the dose of drugs on-the-fly to meet the rapidly changing drug clearance and volume of distribution [15,19].

It is an adaptive dosing method that typically relies on a model-based reinforcement learning method where clinicians gradually increase or decrease drug dosage in response to patient response, or changing physiological state, in a process that resembles expert decision-making [51]. This may also apply the application of AI to know the efficacy and toxicity of different combinations of drugs, which helps in complex polypharmacy that is common in intensive care units [52]. Further, AI is able to discern some of the minute physiological signs that a dysfunction of the organ may happen, and thus pre-emptive changes in drug regimens can be made before clinical decline sets in. The application of the Bayesian prediction software packages to the electronic health records offering evidence-based dosing recommendations is still in development, but it has enormous potential in improving personalized drug administration in the case of critically ill patients [53].

Genetically Polymorphic patients.

Genetic polymorphism has a great influence on drug metabolism and response, and customized dosage regimens are required to enhance the treatment effect of drugs and prevent drug toxicity. Artificial intelligence algorithms and especially those utilizing machine learning can easily spot minor genetic differences between large genomic datasets and match it with drug pharmacodynamics and pharmacokinetics, thus allowing tailored doses to match the individual genetic composition [15]. This sophisticated phenotyping ability commonly involves the use of an unsupervised latent feature learning and makes it possible to identify new groups of patients according to their distinct genetic profiles and responses to drugs, especially with respect to the heterogeneous patients in a critically ill state [54].

These models are able to forecast the metabolizer status of an individual towards certain drugs, such as those that are metabolized by cytochrome P450 enzymes, to enable modifications of prospective dosages to prevent sub-therapy and toxicity. Besides, AI can combine these genetic understandings with clinical information, including age, renal status, and co-morbid drugs to give a comprehensive evaluation of individual drug therapy in genetically heterogeneous groups. The latter is further promoted by the fact that AI can be used to detect trends in large datasets of genetic information and in medical records, allowing predicting how the changes in DNA by genetic variation will impact the cells on a cellular scale [15]. Pharmacogenomics with the help of AI also supports the creation of new pharmacophenotypes where full medication profiles are analyzed in combination with genetic data, which may lead to unexpected discoveries on the correlation between genetic predispositions with drug actions or drug toxicity [54]. This linkage enables having an active attitude towards medication-related matters, when possible drug-gene interactions can be identified prior to the commencement of treatment, thereby reducing adverse effects and maximizing the therapeutic advantages. Combining AI and pharmacogenomics will enable the discovery

of genetic variations that affect drug absorption, metabolism, and efficacy resulting in the optimization of pharmacodynamics and pharmacokinetics [55].

Pharmacokinetic-guided Dosing Tools and Strategies.

This part will explore the sophisticated methodologies and technologies that allow administering individualized drug dosage with high accuracy, and not use a population-based approach but real-time patient data and predictive analytics. The innovations are essential in streamlining of drug therapy particularly in special populations where the conventional dosing schedule might not be effective or even injurious. Such a paradigm shift, which is supported by the development of artificial intelligence and machine learning, enables a dynamic adjustment of doses, depending on the individual peculiarities of physiological reactions, genetic inclination, and objectivity of the environment [37]. In this section, the major tools to be discussed will include the usage of the advanced pharmacokinetic/pharmacodynamic [PK/PD] modeling, therapeutic drug monitoring with the support of the Bayesian forecasting, and the increasingly significant role of artificial intelligence in reflecting the complex patient-specific data to establish individual dosage recommendations. Incorporating AIs and machine learning into these models is transformative, as they help simplify the design of the formulation, improve drug delivery systems, and improve treatment results [27, 56].

Therapeutic Drug Monitoring [TDM]

Therapeutic Drug Monitoring refers to the process of making drug levels in biological fluids to achieve optimum drug exposure in the therapeutic window of a patient so as to maintain balance between efficacy and toxicity. This is especially critical in case of drugs whose therapeutic index is limited and any slight variation of the optimal concentration range may result in serious side effects or even lack of therapy. It employs a multidisciplinary system of clinical monitoring, laboratory evaluation, and pharmacokinetic concepts to make personalized dosage changes. Innovations in AI and machine learning are transforming TDM, as it will allow making more precise predictions of drug pharmacokinetics and individual dosing schedules, using multiple patient-specific parameters including genomics, co-morbidities, and organ functionality [15,23]. These AI applications have the ability to process large volumes of data in order to optimize drug formulations, predict patient responses, and even enable real-time monitoring and adaptive control of drug release so that the therapeutic outcomes are more favourable. In addition, AI systems can optimize their predictions by integrating a new experimental data over and over, thus, constantly improving their usefulness and accuracy in TDM [24]. This allows a shift towards active dose changes as opposed to passive reaction to inappropriate levels of drugs [57].

Population Pharmacokinetics

Population Pharmacokinetic Models: Population pharmacokinetic models enable an individual to gain an insight into drug disposition in a population by describing inter-individual variability and identifying covariates that impact on drug pharmacokinetics [58]. These models use statistical methods, including non-linear mixed-effects modelling, to determine population parameters and measure both fixed and random effects that contribute to variability in drug exposure that is vital in informing the initial dosing decisions in subgroups of patients. This can be used to predict concentrations of drugs under different clinical situations, as well as in special groups where the usual dosage may not be suitable because of differences in physiological processes [59].

Population pharmacokinetic modeling can also be improved by the use of AI and machine learning, which allows identifying more complex associations between various patient attributes and drug disposition and goes beyond conventional covariate analysis to reveal new determinants of pharmacokinetic variability [15]. These sophisticated computational techniques can thus expose more subtle trends of large data thereby resulting in more accurate and individualized dosing regimens than was earlier possible with the traditional pharmacokinetic modeling [60]. Moreover, AI-based computational models can be used to simulate drug

pharmacokinetics and pharmacodynamics, which are essential in the study of drug movement and response within the body and optimize drug development and clinical practice [21]. These innovations are enabled by the fact that with rising access to real-time patient data and advanced data analysis tools, it is now possible to build stronger and predictive models [61].

Pharmacokinetic Simulation and Pharmacokinetic Modeling.

Pharmacokinetic modeling and simulation is a mathematical modeling technique, which uses mathematical models to predict drug levels and effects over a period, so that the dose regimen may be optimized in individual patients and in distinct populations. This requires the development of structural model describing drug absorption, distribution, metabolism, and excretion and simulation has to be done to investigate different dosing conditions and how they affect drug exposure and response [3]. These models frequently make use of the differential equations to model the dynamic processes of drugs movement and transformation in the body and this forms a potent tool in predicting the efficacy of drugs and any probable toxicities [62]. Additionally, more sophisticated machine learning methods can also provide a significant upgrade to the accuracy of such models because they are capable of discovering more complex, non-linear correlations among the pharmacokinetic data than the traditional approaches could do [58].

This integration enables prediction of drug behavior with more accuracy and optimization of drug formulations through high dimensional parameter space screening at high speed [18]. Moreover, the AI algorithms are capable of forecasting the pharmacokinetics and toxicity of drug candidates and thus limit the use of animal testing that is costly and requires extensive testing [20]. Moreover, the process of developing drugs can also be significantly accelerated with the help of AI models that reveal potential drug candidates and optimize their formulations to get to the market and to achieve better patient outcomes faster [21].

Genomic Testing in Pharmacodynamics.

Pharmacogenomics explores the contribution of the genetic composition of a particular person to the drug response, giving important information on the inter-individual differences in drug-pharmacodynamics and drug-pharmacokinetics. It is an area that incorporates genomic testing to detect specific genetic polymorphisms that modify drug-metabolizing enzymes, transporters or receptors to guide individualized dosing schedules to maximize the therapeutic effect and reduce adverse drug reactions [19]. This enables an active response to medication management wherein genetic data can be used to guide drug choice and dose modification even prior to taking medication thereby leaving the empirical dosing approaches. This strategy is further optimized by the introduction of AI and machine learning that allow incorporating complex genomic data with other factors unique to the patients and predicting the pharmacokinetics of drugs with high precision and designing treatment plans that are highly personalized [63].

These AI-powered predictive models are helpful in stratifying patients during the clinical trials, as they help identify those with the highest likelihood of responding to a specific treatment, which hastens drug development and improves precision medicine [24]. The ability of AI to process and analyze large genomic data combined with clinical outcomes just solidifies the effective use of this method in determining drug response and customizing treatment regimens [19,20]. Moreover, disease-related targets can be revealed and their interactions with drug candidates predicted using AI algorithms to optimise drug discovery and development by studying large volumes of biological information, such as genomics and proteomics [20]. This is a holistic analysis, which is reinforced with AI-based methods to reduce the risk of non-clinical toxicity, thus improving the success rate of drug candidates during clinical trials [39].

Software and Algorithms Dosing

The introduction of advanced dosing programs and algorithms has greatly contributed to the implementation of pharmacokinetic principles into clinical practice, which can be real-time modified and used to provide individual therapeutic interventions. They are based on intricate pharmacokinetic frameworks and patient unique data, such as demographic data, physiological metrics and comorbid medications, to prescribe optimal levels of medication that maximize drug benefits and reduces drug effects. A particularly noteworthy example is CURATE.AI, an AI-based platform that dynamically regulates doses of chemotherapy, depending on patient-specific information, which has potential to lower the dose of chemotherapy and prolong the duration and respond rate of patients to chemotherapy in relation to the conventional approach [39].

This type of AI-based tools is crucial in determining subgroups of patients who are more likely to respond favorably to particular treatment thus streamlining trial designs and enhancing the patient outcomes in general [24]. In addition, AI systems can take into consideration a vast amount of details, such as age, weight, genetic composition, and general health of a patient and suggest an ideal dosage that will be specific to the needs of that particular person [19]. This is also applicable to forecasting possible drug-drug interactions and adverse effects, which facilitates patient safety and effectiveness of treatment [34]. These AIs can plot out the complex interaction between intervention intensive and phenotypic effects on the individual patient, which can be used to create highly personalized dosing schedules that can vary with the changing health status of a patient [64]. Moreover, AI in drug formulation and development is another productive development compared to the conventional technology, especially in anticipating drug absorption and excretion profiles [15].

Clinical Uses and Case Analysis.

Antimicrobials among Special Populations.

The use of antimicrobials in special populations is especially difficult to optimize in critically ill patients, neonates, and individuals with organ dysfunction because of the changing pharmacokinetic and pharmacodynamic profiles [65]. As an example, the diversity of patient states, particularly in critically ill patients, requires an individual dosage change in the antibiotic treatment to guarantee treatment effectiveness and avoid development of resistance [66]. With AI-based systems, big volumes of patient reactions toward antimicrobials may be examined by considering personal physiology and pathogen susceptibility to suggest the most effective dose regimens [67]. This has been particularly essential in neonates, where the rapid physiological alterations have a significant effect on drug clearance making the conventional regimes of fixed doses not appropriate. Complex cases represent the field where AI and machine learning could assist healthcare providers in making evidence-based decisions through these cases through extensive analysis of medical literature and drug databases [39].

Cardiovascular Drugs in Special Populations.

Cardiovascular drugs, which are necessary to treat such common conditions as hypertension, heart failure, and arrhythmias, may need complicated dosage changes in the case of special populations because of aging-related physiologic alterations, renal or liver dysfunction, and polypharmacy interactions. Indicatively, in elderly people, renal clearance is often lower, drug sensitivity is often elevated, and as such, the initial dose of drugs like ACE inhibitors or beta-blockers needs to be lower and drugs carefully adjusted to prevent adverse effects. Equally, some cardiovascular drugs have their metabolism slowed in patients with compromised hepatic functions necessitating a dose adjustment to avoid drug build-up and drug toxicity. The inclusion of AI in the clinical scenarios holds great promise to optimize the accuracy of cardiovascular pharmacotherapy through dynamic modeling of each patient response and predicting the most effective dosage changes, according to the real-time data and predictive analytics [15].

This entails the use of AI algorithms to determine optimal cardiovascular drug regimens and reducing adverse events using complex patient data such as genetic predispositions, comorbidities, and concomitant

medications. Patient stratification of cardiovascular therapies can be greatly improved through artificial intelligence by the ability of AI to detect complex relationships among different variables, including gender, genetics, lifestyle and comorbidities [15].

The use of immunosuppressants in Special Populations

Lacking a clear therapeutic index and with a vast range of inter-patient differences in pharmacodynamics and pharmacokinetics, immunosuppressants are also challenging to dose since they are necessary not only to prevent organ rejection in transplant recipients but are also used in managing autoimmune diseases. This fluctuation is further increased in special groups, like pediatric patients or those with compromised kidney or hepatic clearance where extremely individualized dosing plans are required to strike a balance between efficacy and toxicity. Novel AI-based solutions have the potential to analyze an enormous amount of patient data, such as the presence and concentrations of pharmacogenomic markers, drug levels, and patient responses, to infer the most appropriate dose of immunosuppressant medication, reducing the risks of rejection and preventing dose-effect toxicity. Moreover, models driven by AI may help in the comprehensiveness of various formulation variables, which will result in a more efficient and personalized drug delivery system of immunosuppressants [19].

It involves consideration of such factors as comorbidities, organ functioning, which are of utmost importance in patient stratification to therapy and which AI systems can skillfully handle [15]. The fact that AI can review large amounts of patient data, such as genetic predispositions and concomitant drugs, further optimizes these drug prescriptions, providing significant enhancements to conventional approaches [67]. This is more noticeable in the context of kidney transplantation, where machine learning algorithms will be able to predict the required doses of immunosuppressant drugs with a high degree of accuracy, thus resulting in improved health of the organs and better patient outcomes [68]. Also, AI is able to forecast the drug-drug interactions and adverse events unique to immunosuppressants and can be used to implement proactive changes to the treatment plans [67,69].

Antineoplastic Agents in Populations with Special Needs

Antineoplastic agents used in special groups like those with pediatric, geriatric, or renally/hepatically compromised disease have a very tight range of therapeutic indexes and the level of systemic toxicity is severe enough to necessitate the use of very narrow dose adjustments. Conventional fixed dosing plans do not consider the modified pharmacokinetics and pharmacodynamics in these populations, resulting in inefficient results and more chance of severe adverse drug reactions. The advanced method represented by AI and machine learning algorithms provides a solution in the form of individualized dosing schedules based on the specific patient features, genomic background, and real-time physiological information to maximize the effect and reduce the toxicity [19].

Such sophisticated calculation models have the ability to process large amounts of patient information, such as genetic variations that affect drug metabolism, tumor features, and comorbidity profiles, to forecast personal drug reactions and adjust chemotherapy doses based on them [15]. Specifically, reinforcement Learning algorithms have been developed with a growing number of findings that show encouraging effectiveness in dose individualization of anticancer drugs automatically, which can maximize their efficacy and reduce toxicity relative to traditional regimens [70].

This allows a more flexible and patient-centered approach to chemotherapy, which brings to the fore a great improvement in the outcomes of treatment and decreases adverse events in susceptible groups of patients. Also, superior natural language processing algorithms can discover and process unformatted clinical information, including electronic health records and scientific articles, to further optimize dose regimens of antineoplastic agents in more sophisticated patient groups [35]. These types of AI-based approaches enable

significant improvements in the safety and efficacy of cancer treatment in a wide range of patient demographic groups by offering fewer empirically adjusted doses [70].

Special Populations: Analgesics

The special population, such as neonates, pregnant women, and patients with organ dysfunction, also has specific pain management issues and requires extremely personalized analgesic dosage plans. The sophisticated interaction of disturbed pharmacokinetic factors, including a decrease or increase in drug clearance or sensitization to opioids, frequently requires a subtle balance between overtreatment of pain and adverse effects [71]. Machine learning and artificial intelligence have the potential to transform the challenges by predicting patient reactions, maximizing the treatment of pain, as well as reducing side effects, by using data-driven insights [72,73].

Computational models, by incorporating patient-related information, including genetic profiles, physiological parameters, and pain phenotypes, may help clinicians in prescribing medications and dosages that present the best possible outcomes and reduce side effects [74]. Such calculation techniques can determine intricate patterns within a giant amount of data to predict the likelihood of an individual having an opioid use disorder and overdose, which can guide safer prescribing habits [75]. Moreover, AI has the potential to implement a dynamic analgesic regimen based on real-time pain scores and vital signs monitoring, which will result in the most appropriate pain management and a reduced risk of adverse events such as respiratory depression. This is especially important in pediatric pain care where AI systems will be able to anticipate drug reactions through developmental pharmacodynamics and pharmacokinetics and hence provide the correct and safe dosing of children [15]. Furthermore, AI algorithms may anticipate drug-drug interactions and a feature of patients that have high chances of an adverse drug reaction and refine analgesic prescriptions [39].

Difficulties and Future Perspectives

Although the AI and machine learning have great opportunities in enhancing correct dosing of drugs in special populations, a few issues need to be solved to support their popular use in clinical settings. An important challenge includes assuring data quality, integrity, and ethical application of real-world data particularly in case of incorporating different sources such as electronic health records and genomic information [19]. Scarcity is also made more complex by the fact that there are very few labeled datasets of rare diseases or populations with particular traits that can be used to create models of artificial intelligence that are robust and generalizable [24]. Moreover, the black box nature of particular AI algorithms poses a threat to interpretability/transparency which are essential to clinical acceptance and regulatory approval [19].

The solutions to these shortcomings will involve creating explainable AI methods that can give insights into the model predictions, and the creation of standardized data collection guidelines and interdisciplinary partnerships to produce quality and diversified data. Also, it is necessary to rigorously validate AI-supported dosing suggestions in prospective clinical trials to confirm the actual efficacy and safety of AI-supported dosing guidelines in different patient subgroups. The further studies also suggest working on the adaptive AI models that will be able to learn and improve their predictions according to new clinical outcomes and real-world performance and guarantee that drug dosing strategies will keep on optimizing [24]. Additionally, the combination of pharmacogenomics and AI can imply the predictability of individual differences in drug metabolism and response and, therefore, truly personalized medicine in a variety of patient groups. When applied to the neonatal pain management setting, AI-based models can be used to anticipate pain occurrence by examining continuous objective data, namely facial and body movements, frequency of crying, and physiological data, in order to implement non-narcotic interventions on time [76].

Difficulties in Pharmacokinetic Research

Inconvenience of universal protocols to pragmatic pediatric physiologically based pharmacokinetic modelling One of the obstacles to widespread adoption of the model in the development of dosing recommendations is the need to have a clear model of quality assessment and results interpretation. Additionally, there is a need to develop internationally available sites where PBPK modelling information on paediatric pharmacotherapy can be shared to enable the various teams to work together and improve evidence-based decision-making regarding paediatric pharmacotherapy [13]. Additionally, ethical and regulatory issues related to model validation and data privacy are considered to be essential obstacles to the successful implementation of AI into clinical practice [19].

One of such problems is the reliable biomarkers and validation of them in clinical outcomes that requires many data of hundreds of infants, including a wide spectrum of characteristics to make models applicable to the whole population. The introduction of the big data programs, which involve the use of the vital signs data, and important demographic data will be invaluable when it comes to accelerating personalized dosing of the neonates [77]. In addition to neonates, an extension of AI to other vulnerable groups, including critically ill patients, pregnant women, and the elderly, must be done with careful attention to their specific physiological and pathological peculiarities to create specific dosage regimes [15].

The current progress of complex validated dosage regimens combined with therapeutic drug monitoring and Bayesian prognostication is a key milestone towards pharmacotherapy personalization in these groups at risk [78]. This patient-centered method, based on AI and empirical evidence, is critical to reduce the adverse drug reactions and maximize the therapeutic outcomes, as these cohorts of patients exhibit a great physiological disparity [7]. As an example, neonates, because of their inadequate organ activity and altering developmental patterns, display their own pharmacokinetics that requires the application of a special dosing policy, rather than a simple weight change [79].

Clinical Practice Translational Gaps

These developmental variations often result in difficulties in extrapolating adult data on pharmacokinetics and dosing schedules to paediatric patients, and point to an urgent translational void in the evidence-based paediatric pharmacotherapy [13]. It is thus urgently needed to conduct specific studies using sophisticated modelling scenarios and new study designs which would produce solid data used in pharmacokinetics of paediatric specific drug formulations and doses. Moreover, the application of artificial intelligence in this sphere can assist in addressing the problem of data scarcity by using immense volumes of diverse data to extract fine details and determine the most appropriate dosing and thus fill the evidence gap in the areas of paediatric populations [15,22]. These opportunities are provided by AI methods that are most efficient to detect complex relationships between an extended number of variables, such as gender, genetics, lifestyle, and other environmental factors, which are usually ignored in conventional pharmacokinetic modelling. Besides, AI algorithms can combine multimodal patient information, such as co-morbidities and organ functioning, to stratify patients to receive therapy and discover complex connections among various clinical characteristics [15].

Artificial Intelligence and Machine Learning.

The future of pharmacokinetic studies is AI and machine learning that will transform drug development and personalized medicine by expediting drug discovery and optimizing parameters of the formulation [27]. These computing systems are also skilled at predicting drug toxicity and therapeutic effectiveness, hence improving predictive validity of pharmaceutical portals [22]. Studying large volumes of data, AI can determine complex trends that correlate drug characteristics to treatment outcomes, which can help to make more accurate forecasts and speed up the drug development process [27]. In particular, the AI-powered platforms may improve the optimization of drug formulation approach by changing patient demographics or disease trends in real-time. Moreover, the combination of AI and ML practices allows simplifying the

drug development operation tremendously because of reduced trial-and-error testing, which is historically time-consuming and resources-intensive [24]. This optimization is also applied to the ability to predict drug degradation pathways and stability profiles most accurately, which allows much stronger and effective formulations [24]. The use of AI models eases the determination of in vivo responses and pharmacokinetic parameters of therapeutic drugs, which eventually guide the use of the drug by providing the relevant dosing recommendations [15].

Individualized Medicine Projects

The transition to individualized medicine programs, especially in clinical pharmacokinetics, is becoming more and more dependent on AI to tailor the dosage regimen according to the patient-specific traits [27]. AI-based tools are now essential in drug composition and dosage form optimization, using machine learning algorithms and sophisticated data analytics in predicting drug ingredient-excipient interactions [19]. The strategy enables the identification of the best formulations, through the establishment of the best relationships between formulation variables, excipients, and drug properties, thus increasing the chances of formulating strong and effective drug products [24].

In addition, these AI-based approaches facilitate the prompt screening and selection of the best excipients that are essential in the attainment of the desired drug release profiles and bioavailability [21,24]. With a highly precise adjustment of the size, shape, and surface characteristics of nanoparticles, AI allows optimizing the delivery of drugs to target tissues and reducing the off-target effects, which significantly enhances the results of treatment [19,27]. This accuracy is especially useful in targeted therapy and oncology, where targeted drug delivery can greatly decrease systemic toxicity and enhance therapeutic effect [19]. In addition, AI-based methods will play a central role in maximizing the design of various drug delivery systems, increasing the detection of the best drug candidates and drug formulations using high-throughput screening [15] [24]. This allows better and focused drug discovery approach hence improving the chances of successful drug approvals [20].

These developments lead to the development of more efficient, safer and patient-targeted drugs in a broad number of therapeutic fields [21,45]. The latest developments in artificial neural networks and deep learning methods have also made it possible to automate and optimize medication development and distribution systems [21]. This is the primordial technological synergy between AI and pharmacokinetics that changes the development pipeline to a paradigm that is data-driven rather than the empirical approach in quick, efficacious, and eventually safe drug products [15]. The fact that AI can process large amounts of information, such as genetic data, demographics of the patient population, and medications taken by a patient in combination with others, enables an individualized dosing recommendation to be made, which is not based on generalized instructions, but on patient-specific care [45].

Conclusion

The role of clinical pharmacokinetics had been critical in the provision of safe, effective and personalized drug therapy among different groups of patients. This review has indicated the significant effects of differences in physiology, age, disease condition, and genetics on drug absorption, distribution, metabolism, and excretion, especially in special groups of patients, including paediatric, geriatric, pregnant, and critically ill patients. Pharmacokinetic principles had also been incorporated into the clinical practice, thus creating a more accurate dosing, reducing adverse effects, and enhancing the therapeutic outcomes. The use of artificial intelligence [AI] and machine learning [ML] to transform pharmacokinetic modelling was an evangelical step. They were technologies that had improved prediction of the behaviour of drugs under complex physiological conditions, optimization of therapeutic drugs monitoring, and the development of physiologically based pharmacokinetic [PBPK] models. These data-driven methods had enabled clinicians to predict interindividual difference and dynamically modify the dosing regimen including formerly ineligible populations in conventional clinical studies. Nevertheless, some issues were still encountered in applying pharmacokinetic-guided dosing in clinical settings, such as the heterogeneity of data, the lack of

model validation, and ethical issues related to the privacy of the data. To overcome these obstacles, standard modelling frameworks, all-encompassing real-life data integration and interdisciplinary teamwork between pharmacologists, clinicians and data scientists needed to be addressed.

Conflict of Interest

The authors declare they don't have any conflict of interest.

Author contributions

The original author and the supervisor of the cross-ponding author write the first draft of the work. Each author contributed to the article, gathered information, edited it, made tables, and obtained approval before submitting it to a journal for publication.

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Not Applicable

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