

*“ ... the physician's grotesque system – the emptying of miscellaneous and harmful drugs into a person's stomach to remove ailments which in many cases the drugs could not reach at all”*  
Mark Twain, 1900

### Pharmakokinetische Konzepte und ihre Bedeutung für die klinische Medizin

**Zusammenfassung.** In der Geschichte der Medizin findet sich eine große Anzahl von Beispielen für den Kampf von Ärzten mit dem Problem der korrekten Dosierung von Medikamenten. Rezente Studien belegen, dass die mit Arzneimittelgabe-assoziierte Mortalität nach wie vor eine Haupttodesursache darstellt, welche nur durch kardiovaskuläre Krankheiten, Krebs und Schlaganfall übertroffen wird. Zur Rationalisierung der Arzneimitteltherapie wurden in den frühen 70er Jahren pharmakokinetische Prinzipien der Arzneimitteldosierung, hauptsächlich in Form des Therapeutic Drug Monitoring (TDM) in die klinische Praxis eingeführt, eine Maßnahme, die zu einer Reduktion der Arzneimittel-assoziierten Mortalität geführt hat. Inhärente Limitationen der traditionellen Pharmakokinetik (PK) führten jedoch bei vielen Ärzten zur Ansicht, dass klinische PK eine Fleißaufgabe mit beschränkter klinischer Relevanz sei. Trotz dieser Vorstellung kam es in den letzten Jahren zu einigen bemerkenswerten Entwicklungen, die aus dem Gebiet der klinischen PK eine auf physiologischen Mechanismen basierende Disziplin mit wichtigen Implikationen für die klinische Medizin gemacht haben. Insbesondere konnte durch die neuen Konzepte (1) PK-PD (Pharmakokinetik-Pharmakodynamik)-Modeling, (2) Zielgewebs-PK, (3) Populations-PK und (4) Pharmakogenetik eine bessere Integration pharmakokinetischer Prinzipien in die klinisch pharmakologische Therapie ermöglicht werden. Der vorliegende Artikel versucht einen Einblick in diese Entwicklungen und deren Bedeutung für das allgemeine Verständnis der Arzneimitteltherapie zu geben.

\* supported by FWF-grant J1895 Med

**Schlüsselwörter:** Klinische Pharmakokinetik, klinische Pharmakodynamik, Dosierung, Gegenwärtige Konzepte.

**Summary.** The history of medicine provides evidence of the physicians' struggle with the suboptimal and inappropriate drug dosing. Recent studies indicate that drug-related mortality due to inadequate dosing and toxicity still is a leading cause of death, only surpassed by cardiovascular diseases, cancer and stroke. In an effort to rationalize drug therapy, pharmacokinetic (PK) and pharmacodynamic (PD) principles were introduced in medical practice in the early 1970s, mainly in the field of therapeutic drug monitoring (TDM). This measure was shown to reduce mortality. Several innovations in traditional PK, however, have led to the realization among many physicians that clinical PK is an unnecessary assignment of limited clinical relevance. Due to perceived limitations of traditional PK research, considerable developments have taken place in recent years. These have made clinical PK a “physiological-mechanistic endeavor” with important implications for clinical practice. Notably, the introduction of (1) PK-PD (pharmacokinetic-pharmacodynamic) modeling (2) target site pharmacokinetics (3) population PK and (4) pharmacogenomics has permitted a better integration of PK principles into clinical drug therapy. The aim of the present article is to provide an overview of these developments and to discuss their impact on our understanding of clinical drug therapy.

**Key words:** Clinical pharmacokinetics, clinical pharmacodynamics, drug dosing, current concepts.

### Introduction

*A brief historical view of clinical pharmacokinetics*

The word “pharmacokinetics” is derived from the Greek words “pharmakon” (drug) and “kinesis” (movement) and was first mentioned in a textbook by the Geriatrician Friedrich Hartmut Dost in 1953 [1]. The author paid credit to recent advances in a newly established discipline which tried to describe the events that govern the behavior of a drug in the human body. One of the first applica-

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8–20] – including eminent personalities like Vincent van Gogh [20], Wolfgang Amadeus Mozart [16, 17, 19] and Nicolo Paganini [18]. It was often not clear whether a patient died due to the disease itself or due to the cure that was administered by the physician. This unfortunate situation led Mark Twain in 1900 to decry “.. the physician’s grotesque system – the emptying of miscellaneous and harmful drugs into a person’s stomach to remove ailments which in many cases the drugs could not reach at all” [21]. In the subsequent decades, physicians struggled with the subject of appropriate drug administration. Digitalis was a notoriously “difficult to dose drug” [20] and the narrow effect side effect profile was well known to readers of Agatha Christie thrillers, in which digitalis was used 6 times in a total of 83 cases of lethal poisoning [20]. Similar to digoxin, the synthetic antimalarial agent quinacrine which was developed during World War II as a substitute for the scarce quinine, was either ineffective or produced unacceptable toxicity [22]. Only after its pharmacokinetics (PK) was described and it was realized that large doses had to be given initially, followed by small daily doses, could quinacrine be used successfully [22]. An abundance of similar experiences with different drugs led to the development of an independent research field of clinical PK. From 1950 to 1980 the science of PK became an integral part of drug development and also assumed a significant role in clinical practice [5, 23].

#### *Current status of PK in clinical drug use*

Clinical PK emerged as a clinical discipline in the early 1970s. Initially it was largely concerned with therapeutic drug monitoring (TDM), i.e. the measurement of plasma drug concentrations to guide drug dosing. Drugs usually are suitable candidates for TDM, provided they have substantial pharmacokinetic variability, a narrow therapeutic index, and provided a concentration-effect relationship is established. Commonly monitored drugs are aminoglycosides, vancomycin, teicoplanin, theophylline, methotrexate, digitalis glycosides, cyclosporin, and several antiepileptic agents. TDM was advocated for optimizing the use of other selected drugs as well [24]. The widespread acceptance of clinical PK in the pharmaceutical care process was triggered by reports on reduced mortality, shorter duration of treatment and hospital stay, decreased morbidity, and less adverse effects from drug therapy due to TDM [25].

current principles of drug therapy might be suboptimal, adverse drug reactions are a leading cause of death in hospitals [29–32]. It was shown that 0.32% of hospitalized patients became victims of fatal ADRs. Consequently the authors estimated that, in the USA, 106,000 patients per year had fatal ADRs, making these reactions the fourth leading cause of death, only surpassed by cardiovascular disease, cancer and stroke [29]. This rather alarming finding, which is not very much unlike the situation in the times of Mozart and Paganini, was attributed in part to insufficient knowledge of PK principles and individual dosing principles in many clinical specialties [29]. Interestingly, programs that survey drug therapy according to clearly stated principles were shown to reduce the number of drugs per patient, the number of drugs in hospital and also the number of ADRs [20, 25, 31, 33–35].

#### *Current status of PK in drug development and drug use*

Whereas PK principles were rather hesitantly embraced in routine care, they are of paramount importance in drug development [36, 37]. Clinical drug development programs are faced with the challenge of identifying early on those drug candidates that will successfully make it through the costly and time-consuming phase III and eventually enter the market. Experience shows that reasons for candidate attrition are varied and include problems related to tolerability, pharmacokinetics and lack of adequate effectiveness [37]. While in some instances tolerability problems cannot be spotted until large numbers of patients have been exposed, discontinuation of a development program due to poor pharmacokinetic (PK) properties usually occurs early during phase I/II studies. The fact that even today candidate development is sometimes discontinued merely for (predictable) PK-related reasons during or after phase III [38] testifies to the importance of PK characterization by clinical management.

#### **Traditional concepts in clinical PK – descriptive pharmacokinetics**

##### *The old dream of an optimal dose*

Dose individualization, i.e. giving the right dose to the right patient, has long been a preoccupation of clinical pharmacologists who justly railed against the common practice of administering a standard dose to all patients

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ance of antileukemic agents, which usually differs by a factor of 3 to 10, is an important predictor of outcome [26]. Outcome could be improved when doses were individualized to prevent low systemic exposure to the drugs in patients with fast drug clearance. Children who received individualized therapy had a significantly better outcome than did those given conventional therapy, and the time-dependent systemic exposure to methotrexate was significantly related to the risk of early relapse [26].

#### *The traditional LADME system and its limitations*

PK studies are usually tailored to the characteristics of the individual drugs in order to obtain as much information as possible on so-called LADME events, i.e. liberation (L), absorption (A), distribution (D), metabolism (M) and elimination (E). Traditional PK approaches have provided a large body of information on LADME events, which have had a major influence on the drug armamentarium that is available to combat various diseases.

One limitation of traditional LADME studies was fact that they were focused on plasma concentration measurements and paid little attention to the distribution of the substance into the anatomically defined target site. Whereas L, A, M, and E events were described directly for many years, D events could not be measured directly and were usually indirectly modeled from plasma concentration curves. This approach implied a seldom communicated consensus on the fact that concentrations in so-called “deep” or “shallow” compartments have no actual anatomical correlate and do merely represent virtual values in hypothetical spaces. Although plasma-based modeling procedures help us to understand certain principles of drug distribution, their value is clearly limited if plasma and tissues are not in full equilibrium, as is the case in blood-tissue barriers e.g. in the brain. However, it should be remembered that a number of other barriers besides the blood brain barrier exist in the body, e.g. blood-prostate, blood-eye, blood-ear, blood-placenta or blood-tumor barriers [40–43], which either develop physiologically during organogenesis or might develop during pathological processes. Other limitations of traditional PK approaches were the need for rich data sets in individual patients, the lack of predictability for the variability encountered in the population, and a paucity of models that would allow for correlating concentration values to drug effects.

Most of these limitations have also led to the belief

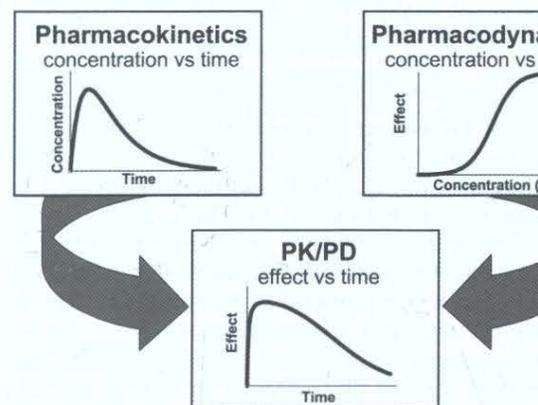
the above mentioned limitations of the traditional clinical PK system have been resolved by the introduction of novel methodologies. Thus we have entered a phase in which clinical PK has indeed become a “physiological-mechanism based endeavor” [5] with important implications for clinical medicine.

#### **Novel concepts in clinical PK – predicting pharmacokinetics**

In recent years 4 new developments in PK have led to major advances in understanding and defining drug therapy, i.e. (1) PK-PD (pharmacokinetics-pharmacodynamics) modeling by the integration of drug effects, (2) population PK by the integration of population variability, (3) target site PK by integrating anatomically defined distribution, and (4) pharmacogenomics by truly individualizing individual PK parameters.

##### *1. Integrating drug effects – PK-PD modeling*

It was realized that the usefulness of mere PK studies is quite limited if PK is viewed isolated from pharmacodynamics. The science of PK/PD creates a bridge between these 2 classical disciplines of clinical pharmacology.



**Fig. 1.** Basic concept of the PK-PD (pharmacokinetic-pharmacodynamic) approach. Based on time versus concentration measurements (top, left panel) and known relationships between drug receptor effects and drug concentrations (top, right panel), an integrated model is constructed that allows for a more variant description of the effect profile (bottom panel).

icel routine, as it became clinical practice to administer gentamicin as a high dosed i.v. bolus – rather than as an i.v. infusion with plasma concentrations above a static threshold value – the MIC. Long times above MIC threshold values do not contribute to increased efficacy and lead to severe side effects. Aminoglycosides are a good example to demonstrate that the effect and side effect profiles of drugs may be determined by different PK profiles, and that it makes good sense to elucidate such mechanisms in order to fully exploit the therapeutic options of a given drug.  $\beta$ -lactams, in contrast, should be administered in a way as to keep target site concentrations above MIC values without sub-MIC windows [46]. A further example of the usefulness of PK-PD in clinical practice was the realization that the infusion rate of nifedipine is an important determinant of its antihypertensive effect. Due to reflex mechanisms, the same dose given as a fast release formulation is much less effective than when it is administered as a slow release formulation [47]. Similar relationships which could help to dissociate therapeutic effect and side effects were described for 5-fluorouracil; continuous infusion led to a better effect / side-effect profile than bolus administration [48].

### 2. Integrating population variability – Population PK

Population pharmacokinetics (Pop PK) is the study of the sources and correlates of variability in drug concentrations among patients. Certain demographic or pathophysiological features such as body weight, excretory and metabolic function and disease characteristics are liable to alter dose-concentration relationships. However, PK data were frequently obtained from healthy volunteers and it is questionable whether these data reflect those in a given patient population. In fact, it was realized that the variability that occurs in the “real life” clinical situation is critical for drug therapy and the occurrence of adverse events [49, 50].

Pop. PK aims at collecting PK data from patients who are representative of the target population to be treated, tries to identify and explain causes for variability and gives a quantitative estimate of unexplained variability. This approach is currently gaining importance in drug development and the FDA reported that, in the fiscal years 1995 and 1996, one quarter of new drug submissions contained pop. PK data sets [50]. The mathematical background of

ments from several individuals (top panels) an integrated model is constructed. The model allows for a time variant description of the concentration profile and enables the investigator to relate pharmacokinetic variability to individual parameters such as clearance, weight or disease status (bottom panel)

pop. PK is relatively complex. The principle is to compare individual concentration data sets with the collective data set and to regard individual parameters such as weight and individual specific covariates. The probability of distribution of the concentration data is then modeled as a function of these covariates. One major advantage of pop. PK is that the approach is also feasible for sparse data sets, i.e. when only few data points are available per patient (Fig. 2). The pop. PK approach is particularly useful for defining the influence of physiological as well as pathological conditions on PK in a target collective of patients

### 3. Integrating drug distribution – target site PK

Most drugs, with few notable exceptions such as heparin, exert their effects not within the plasma compartment but in defined target tissues into which drugs will have to distribute from the central compartment. Unfortunately a complete and lasting equilibration between blood and tissue can by no means be taken for granted [40–45] and several studies have shown that tissue concentrations are more predictive of outcome than plasma concentrations [52, 53]. This fact, which is best established for CNS diseases, is also taken into account in locoregional strategies for drug application e.g. intraarterial or intrathecal chemotherapy [54].

Despite the perceived inability to directly measure drug concentrations in tissues, several clinical methods have become available, which enable us to trace the path of a drug within the human body [37, 52–58]. Autoradiography, post mortem organ sampling and homogenization have been available for many decades and yield some information on drug distribution into individual organs but, for obvious ethical reasons, were frequently off limits for clinical drug studies. The last few years have witnessed the development of novel techniques that are suitable to study tissue PK in humans, i.e. magnetic resonance spectroscopy (MRS, [52]), single photon emission computed tomography (SPECT, [55]), positron emission tomography (PET [56], Fig. 3) and in vivo microdialysis [45, 58]. By applying these techniques to clinical studies it b

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**Fig. 3.** Representative PET images of human subjects following administration of [18F]trovafloxacin. The area of maximum tissue trovafloxacin concentration on each image is represented as 100% on the color scale. Reprinted from Fischman et al. "Pharmacokinetics of [18F]Trovafloxacin in Healthy Human Subjects Studied with Positron Emission Tomography", *Antimicrobial Agents and Chemotherapy*, August 1998, pp 2048-2054, Vol. 42, No. 8; with permission from the American Society for Microbiology

came obvious that the previously neglected drug distribution process to the target site might be an important determinant of clinical outcome and contributes more to variability in the dose-effect relationship than variability in plasma PK.

#### 4. Integrating individual parameters-pharmacogenomics

Physicians have long recognized a familial clustering of unusual responses to drugs. In 1957 Motulsky published an article on a number of genetic conditions as the cause for a toxic reaction to a drug or an environmental chemical [59]. Vessel and Page showed that the large interindividual variability in PK vanished within sets of monozygotic twins [60, 61]. Genetic polymorphisms may occur at different levels in the drug-effect cascade, i.e. at the level of drug targets like receptors, at the level of disease pathways or at the level of drug metabolism [62]. Genetic polymorphisms of metabolic enzymes are important determinants of PK profiles and, thereby, also of toxicity and drug response [62].

The first pharmacogenetic discovery that became a routine aspect of medical practice was the observation that hemolysis was more common among African-American soldiers in the United States Army who were taking the antimalarial primaquine during World War I. Subsequent studies revealed a genetic deficiency of glucose-6-phosphate dehydrogenase as the reason for this serious side effect and it became good medical practice to screen patients for this enzyme defect prior to initiating primaquine therapy [63]. One example for genetic determination of a clinically relevant PK profile is intolerance to 6-mercaptopurine, a standard anti-ALL drug. Extreme intolerance was shown among patients with deficiencies in thiopurine S-

methyltransferase (TPMT) enzyme activity. R doses of 6-mercaptopurine in TPMT heterozygote deficient patients permitted the administration of protocol doses of other kinds of chemotherapy while maintaining high thioguanine nucleotide concentrations. Genotyping, or functional enzyme analysis, has become standard practice in major cancer treatment centers as the Mayo Clinic in Rochester and St. Jude's Children's Research Hospital in Memphis [64]. Pharmacogenomics has also provided a number of useful surrogate markers for disease-drug interactions such as polymorphisms for the ACE gene and responsiveness to ACE inhibitors, mutations in potassium channel genes and their interaction with drug induced long-QT syndromes, expression of HER2/neu and benefit of adjuvant chemotherapy in breast cancer or polymorphisms in 5-HT<sub>2A</sub> receptors, and resistance to antipsychotic drugs [62].

The opportunities created by recent conceptual and methodological advances in molecular biology will have a great impact on drug therapy [65]. Most important will be the ability to select optimal drug candidates for individual patients and avoid unnecessary adverse events by identifying a fingerprint of the patient's individual genetic

#### Conclusions and outlook on the role of pharmacogenomics in principles for patient care

Clinical PK is and will be increasingly regulated by the above developments and by a further refinement of analytical and computational facilities. Thus, by extending the last 10 years of PK research it is very likely that different trends will emerge in the future.

(1) The revolution in genetics will allow for a true individualization of drug therapy. This development

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