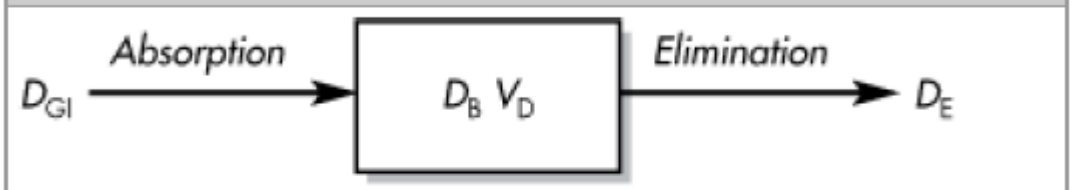
PHARMACOKINETICS OF DRUG ABSORPTION

In pharmacokinetics, the overall rate of drug absorption may be described as either a first-order or zero-order input process. Most pharmacokinetic models assume first-order absorption unless an assumption of zero-order absorption improves the model significantly or has been verified experimentally.

The rate of change in the amount of drug in the body, *dD* B/*dt*, is dependent on the relative rates of drug absorption and elimination . The net rate of drug accumulation in the body at any time is equal to the rate of drug absorption less the rate of drug elimination, regardless of whether absorption is zero-order or first order.

Figure 7-1.



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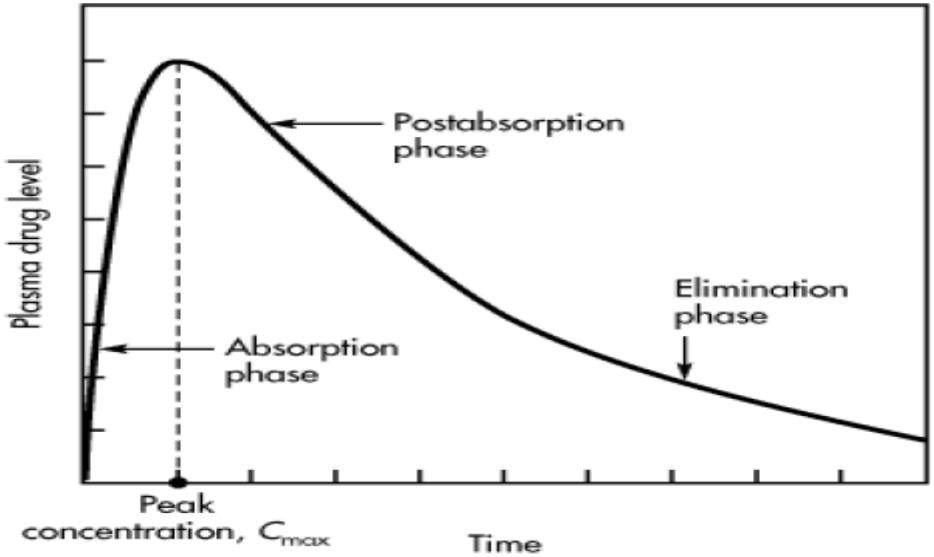
Model of drug absorption and elimination.

$$\frac{dD_B}{dt} = \frac{dD_{GI}}{dt} - \frac{dD_E}{dt} \qquad (7.1)$$

Where *D* GI is amount of drug in the gastrointestinal tract and *D*E is amount of drug eliminated. A plasma level time curve showing drug absorption and elimination rate processes is given in . During the *absorption phase* of a plasma level time curve, the rate of drug absorption is greater than the rate of drug elimination. Note that during the absorption phase, elimination occurs *whenever* drug is present in the plasma, even though absorption predominates.



Plasma level time curve for a drug given in a single oral dose. The drug absorption and elimination phases of the curve are shown.

$$\frac{dD_{GI}}{dt} > \frac{dD_E}{dt} \qquad (7.2)$$

At the *peak drug concentration* in the plasma the rate of drug absorption just equals the rate of drug elimination, and there is no net change in the amount of drug in the body.

$$\frac{dD_{GI}}{dt} = \frac{dD_E}{dt} \qquad (7.3)$$

Immediately after the time of peak drug absorption, some drug may still be at the absorption site (ie, in the GI tract or other site of administration). However, the rate of drug elimination at this time is faster than the rate of absorption, as represented by the ***postabsorption phase*** in .

$$\frac{dD_{GI}}{dt} < \frac{dD_E}{dt} \qquad (7.4)$$

When the drug at the absorption site becomes depleted**, the rate of drug absorption approaches zero, or *dD* GI/*dt* = 0**. The plasma level time curve (now the *elimination phase*) then represents only the elimination of drug from the body, usually **a first-order process.** Therefore, during the elimination phase the rate of change in the amount of drug in the body is described as a first-order process,

$$\frac{dD_B}{dt} = -kD_B \qquad (7.5)$$

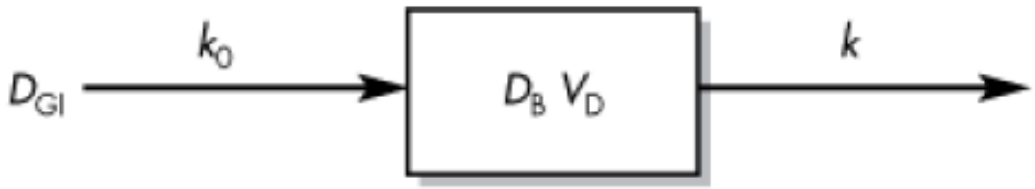
where *k* is the first-order elimination rate constant.

ZERO-ORDER ABSORPTION MODEL

Zero-order drug absorption from the dosing site into the plasma usually occurs when either the drug is absorbed by a **saturable process or a zero-order controlled-release delivery system is used.** In this model, drug in the gastrointestinal tract, *D* GI, is absorbed systemically at a **constant rate, *k*0**. Drug is simultaneously and immediately eliminated from the body by a first-order rate process defined by a first-order rate constant, *k*.

This model is analogous to that of the administration of a drug by intravenous infusion.

Figure 7-3.



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One-compartment pharmacokinetic model for zero-order drug absorption and first-order drug elimination.

The rate of first-order elimination at any time is equal to *D* B*k*. The rate of input is simply *k* 0. Therefore, the net change per unit time in the body can be expressed as Integration of

$$\frac{dD_B}{dt} = k_0 - kD_B \qquad (7.6)$$

Integration of this equation with substitution of *V*D *C*p for *D*B produces

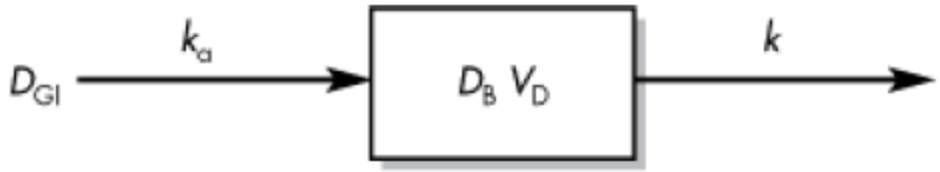
$$C_P = \frac{k_0}{V_D k}(1 - e^{-kt}) \qquad (7.7)$$

The rate of drug absorption is constant until the amount of drug in the gut, *D*GI, is depleted. **The time for complete drug absorption to occur is equal to *D*GI/*k* 0**. After this time, the drug is no longer available for absorption from the gut, and Equation 7.7 no longer holds. The drug concentration in the plasma subsequently declines in accordance with a **first-order elimination rate process.**

FIRST-ORDER ABSORPTION MODEL

Although zero-order absorption can occur, absorption is usually assumed to be a first-order process. This model assumes a first-order input across the gut wall and first-order elimination from the body. This model applies mostly to the oral absorption of drugs in **solution or rapidly dissolving dosage (immediate release) forms such as tablets, capsules, and suppositories. In addition, drugs given by intramuscular or subcutaneous aqueous injections may also be described using a first-order process**.

Figure 7-4.



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One-compartment pharmacokinetic model for first-order drug absorption and first-order elimination.

In the case of a drug given orally, **the dosage form first disintegrates if it is given as a solid, then the drug dissolves into the fluids of the GI tract**. Only drug in solution is absorbed into the body. The rate of disappearance of drug from the gastrointestinal tract is described by

$$\frac{dD_{GI}}{dt} = -k_a D_{GI} F \qquad (7.8)$$

where *k*a is the first-order absorption rate constant from the GI tract, *F* is the fraction absorbed, and *D* GI is the amount of drug in solution in the GI tract at any time *t*. Integration of the differential equation (7.8) gives

$$\frac{dD_{GI}}{dt} = -k_a D_{GI} F \qquad (7.8)$$

$$\frac{dD_{GI}}{dt} = D_0 e^{-k_a t} \qquad (7.9)$$

where *D*0 is the dose of the drug. The rate of drug elimination is described by a first-order rate process for most drugs and is equal to *kD*B. The rate of drug change in the body, *dD*B/*dt*, is therefore the rate of drug in, minus the rate of drug out as given by the differential equation, Equation 7.10:

$$\frac{dD_B}{dt} = \text{rate in} - \text{rate out}$$

$$\frac{dD_B}{dt} = Fk_a D_{GI} - kD_B \qquad (7.10)$$

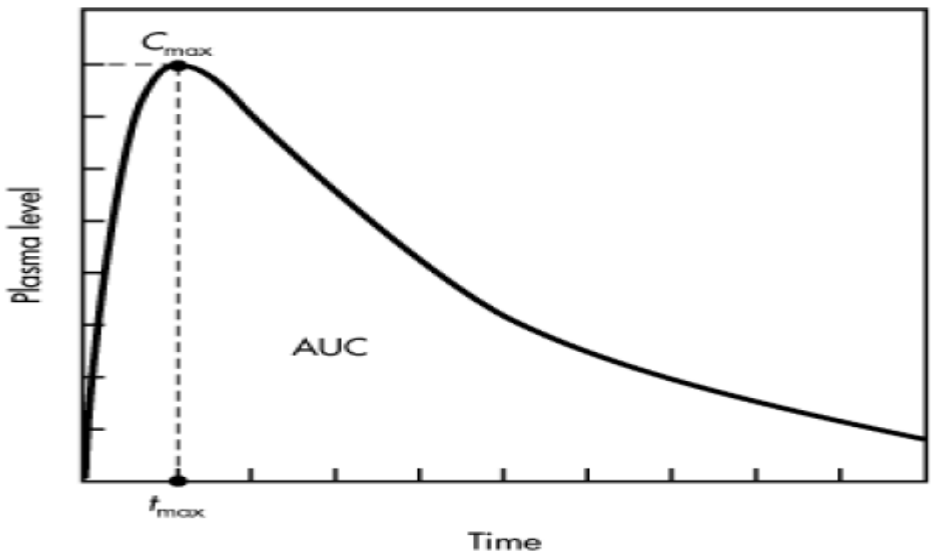
where *F* is the fraction of drug absorbed systemically. Since the drug in the gastrointestinal tract also follows a first-order decline (ie, the drug is absorbed across the gastrointestinal wall), the amount of drug in the gastrointestinal tract at any time *t* is equal to $D_0 e^{-kat}$.

$$\frac{dD_B}{dt} = Fk_a D_0 e^{-k_a t} - kD_B$$

The value of ***F*** **may vary from 1 for a fully absorbed drug to 0 for a drug that is completely unabsorbed**. <u>This equation can be integrated to give the general oral absorption equation for calculation of the drug concentration (*C* p) in the plasma at any time *t*, as shown below</u>.

$$C_P = \frac{Fk_a D_0}{V_D (k_a - k)} (e^{-kt} - e^{-k_a t}) \qquad (7.11)$$

A typical plot of the concentration of drug in the body after a single oral dose is presented in



The maximum plasma concentration after oral dosing is *C* max, and the time needed to reach maximum concentration is *t* max. **The *t* max is independent of dose and is dependent on the rate constants for absorption (*k*a) and elimination (*k*) (Eq. 7.13a).** At *C*max, sometimes called ***peak concentration***, the rate of drug absorbed is equal to the rate of drug eliminated. Therefore, the net rate of concentration change is equal to zero. **At *C* max, the rate of concentration change can be obtained by differentiating Equation 7.12, as follows:**

$$C_P = \frac{F k_a D_0}{V_D (k_a - k)} (e^{-kt} - e^{-k_a t}) \qquad (7.11)$$

$$dC_p/dt = \frac{k_a D_0 F}{V_D (k_a - k)} (-ke^{-kt} + k_a e^{-k_a t}) = 0 \qquad (7.12)$$

This can be simplified as follows:

$$-ke^{-kt} + k_a e^{-k_a t} = 0 \qquad \text{or} \qquad ke^{-kt} = k_a e^{-k_a t} \qquad (7.13)$$

$$\ln k - kt = \ln k_a - k_a t$$

$$t_{max} = \frac{\ln k_a - \ln k}{k_a - k} = \frac{\ln (k_a / k)}{k_a - k}$$

$$t_{max} = \frac{2.3 \log (k_a / k)}{k_a - k} \qquad (7.13a)$$

As shown in Equation 7.13a, the time for maximum drug concentration, ***t* max, is dependent only on the rate constants *k*a and *k***. In order to calculate ***C* max, the value for *t*max** is determined via Equation 7.13a and then substituted into Equation 7.11, solving for *C* max. Equation 7.11 shows that **Cmax is directly proportional to the dose of drug given (*D*0) and the fraction of drug absorbed (*F*).** Calculation of *t* max and *C* max is usually necessary, **since direct measurement of the maximum drug concentration may not be possible due to improper timing of the serum samples.**

The first-order elimination rate constant may be determined from the elimination phase of the plasma level time curve. **At later time intervals**, when drug absorption has been completed, ie, *kat* , Equation 7.11 reduces to

$$C_P = \frac{F k_a D_0}{V_D (k_a - k)} e^{-kt} \qquad (7.14)$$

Taking the natural logarithm of this expression,

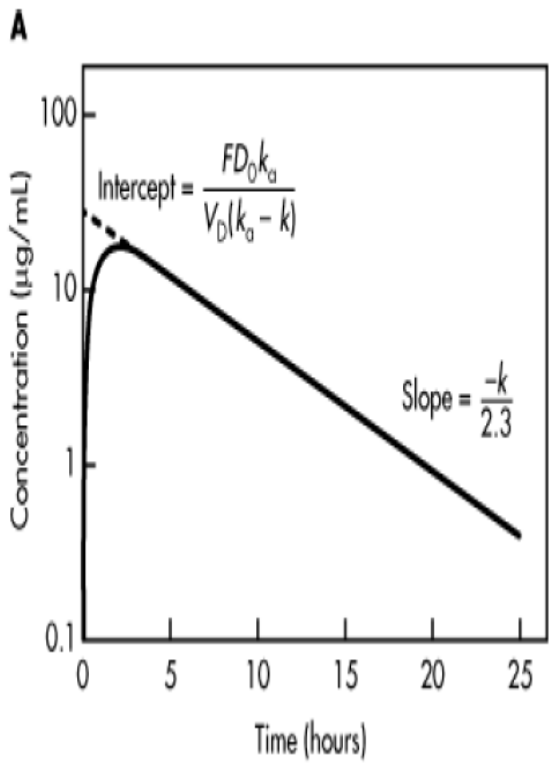
$$\ln C_P = \ln \frac{F k_a D_0}{V_D (k_a - k)} - kt \qquad (7.15)$$

Substitution of common logarithms gives

$$\log C_p = \log \frac{F k_a D_0}{V_D (k_a - k)} - \frac{kt}{2.3} \qquad (7.16)$$

With this equation, a graph constructed by plotting log *C* p versus time will yield a straight line with a slope of *k*/2.3.

Figure 7-6.



Determination of Absorption Rate Constants from Oral Absorption Data
METHOD OF RESIDUALS

Assuming *k* a >> *k* in Equation 7.11, the value for the second exponential will become insignificantly **small with time (ie, $e^{-kat} \approx 0$)** and can therefore be omitted. When this is the case, drug absorption is virtually complete. Equation 7.11 then reduces to Equation 7.22.

$$C_P = \frac{F k_a D_0}{V_D (k_a - k)} e^{-kt} \qquad (7.22)$$

From this, one may also obtain the intercept of the *y* axis

$$\frac{F k_a D_0}{V_D (k_a - k)} = A$$

where *A* is a constant. Thus, Equation 7.22 becomes

$$C_P = A e^{-kt} \qquad (7.23)$$

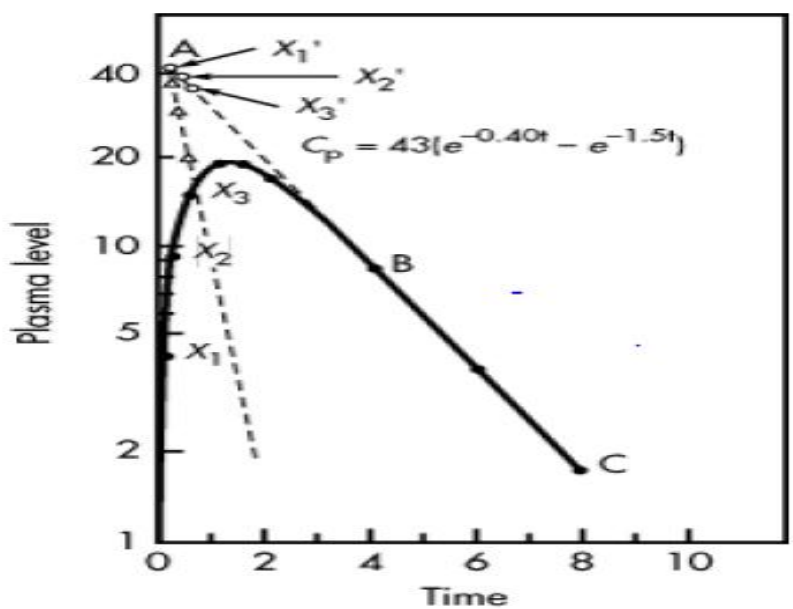
This equation, which represents first-order drug elimination, will yield a linear plot on semilog paper. The slope is equal to -*k*/2.3. The value for *k*a can be obtained by using the **method of residuals or a feathering** technique, as described in . The value of *k*a is obtained by the following procedure:

1. Plot the drug concentration versus time on semilog paper with the concentration values on the logarithmic axis.

2. Obtain the slope of the terminal phase (line *BC*,) by extrapolation.

3. Take any points on the upper part of line *BC* (eg, *x*'1, *x*'2, *x*'3, . . .) and drop vertically to obtain corresponding points on the curve (eg, *x* 1, *x* 2, *x* 3, . . .).

4. Read the concentration values at *x* 1 and *x*'1, *x* 2 and *x*'2, *x* 3 and *x*'3, and so on. Plot the values of the differences at the corresponding time points 1, 2, 3, ... A straight line will be obtained with a slope of -*k* a/2.3.



When using the method of residuals, **a minimum of three points should be used to define the straight line.**

Data points occurring shortly after *t* max may not be accurate, because drug absorption is still continuing at that time. Because this portion of the curve represents **the postabsorption phase, only data points from the elimination phase should be used to define the rate of drug absorption as a first-order process**.

If drug absorption begins immediately after oral administration, **the residual lines obtained by feathering the plasma level time curve will intersect on the *y* axis at point *A*.**

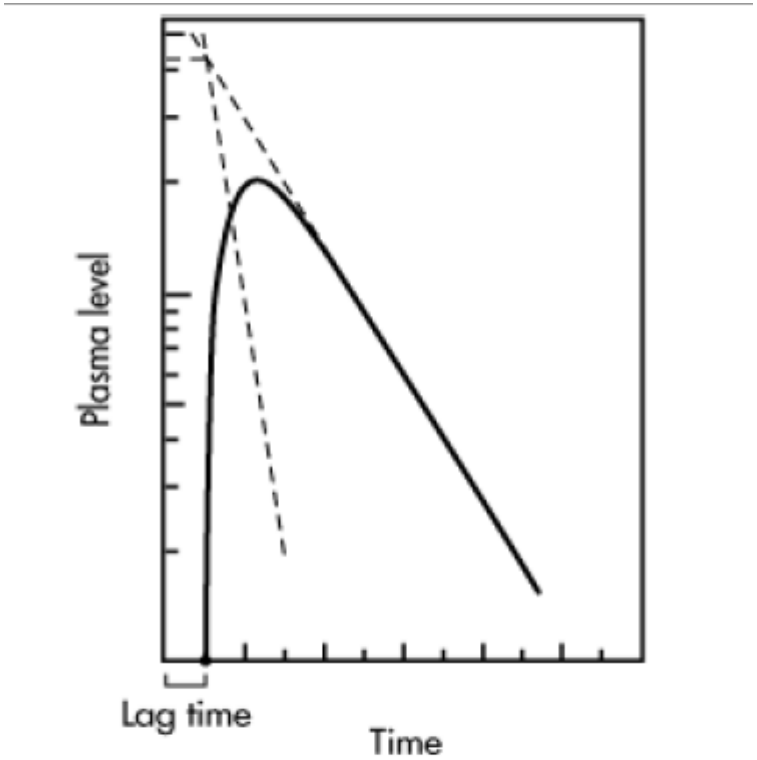
The value of this *y* intercept, *A*, represents **a hybrid constant composed** of *k*a, *k*, *V* D, and *FD*0. The value of *A* has no direct physiologic meaning (see Eq. 7.23).

$$A = \frac{F k_a D_0}{V_D (k_a - k)}$$

LAG TIME

In **some individuals**, absorption of drug after a single oral dose does not start immediately, due to such physiologic factors as **stomach-emptying time and intestinal motility.** The time delay prior to the commencement of first-order drug absorption is known **as *lag time***.

The lag time for a drug may be observed if the two residual lines obtained by feathering the oral absorption plasma level time curve intersect at a point greater than *t* = 0 on the *x* axis. The time at the point of intersection on the *x* axis is the lag time.



The lag time, t_0, represents the beginning of drug absorption and should not be confused with the pharmacologic term *onset time*, which represents latency, eg, the time required for the drug to reach minimum effective concentration.

Two equations can adequately describe the curve in . In one, the lag time t_0 is subtracted from each time point, as shown in Equation 7.24.

$$C_P = \frac{Fk_a D_0}{V_D(k_a - k)}\left(e^{-k(t-t_0)} - e^{-k_a(t-t_0)}\right) \qquad (7.24)$$

where *Fk*a *D*0/*V* D(*k*a-*k*) is the *y* value at the point of intersection of the residual lines in Figure of lag time.

The second expression that describes the curve in the Figure of lag time omits the lag time, as follows:

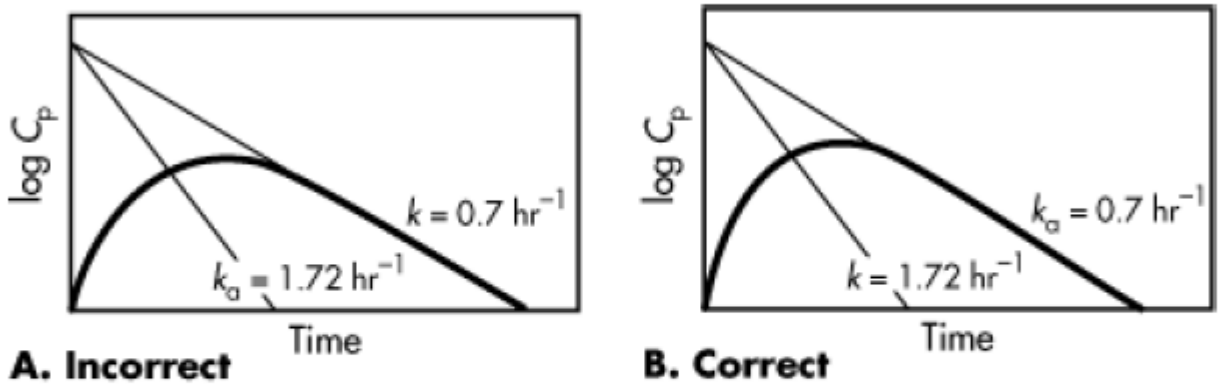
$$C_P = Be^{-kt} - Ae^{-k_a t} \qquad (7.25)$$

<u>where *A* and *B* represents the intercepts on the *y* axis after extrapolation</u> of the residual lines for absorption and elimination, respectively.

FLIP-FLOP OF Ka AND K

In using the method of residuals to obtain estimates of *k*a and *k*, the terminal phase of an oral absorption curve is usually represented by *k* whereas the steeper slope is represented by *k*a. **<u>In a few cases, the elimination rate constant *k* obtained from oral absorption data does not agree with that obtained after intravenous bolus injection</u>**. For example, the *k* obtained after an intravenous bolus injection of a bronchodilator was 1.72 hr^{-1}, whereas the *k* calculated after oral administration was 0.7 hr^{-1}. When *k*a was obtained by the method of residuals, the rather surprising result was that the *k*a was 1.72 hr^{-1}

Figure 7-11.



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Flip-flop of k_a and *k*. Because $k > k_a$, the right-hand figure and slopes represent the correct values for k_a and *k*.

For drugs that have a large elimination rate constant ($k > 0.69\ hr^{-1}$), the chance for flip-flop of *k*a and *k* is much greater. The drug isoproterenol, for example, has an oral elimination half-life of only a few minutes, and flip-flop of *k*a and *k* has been noted. Similarly, salicyluric acid was flip-flopped when oral data were plotted

Apparently, **the *k*a and *k*** obtained by the method **of residuals** has been interchanged. This phenomenon is called ***flip-flop*** of the absorption and elimination rate constants. Flip-flop, or **the reversal of the rate constants**, may occur whenever *k*a and *k* are estimated from oral drug absorption data. Use of computer methods does not ensure against flip-flop of the two constants estimated. In order to demonstrate unambiguously that the steeper curve represents the elimination rate for a drug given extravascularly**, the drug must be given by intravenous injection into the same patient. After intravenous injection, the decline in plasma drug levels over time represents the true elimination rate.**

Most of the drugs observed to have flip-flop characteristics are drugs with **fast elimination** (ie, $k > ka$