International Union of Pharmacology Committee on Receptor Nomenclature and Drug Classification. XXXVIII. Update on Terms and Symbols in Quantitative Pharmacology

RICHARD R. NEUBIG, MICHAEL SPEDDING, TERRY KENAKIN, AND ARTHUR CHRISTOPOULOS

Department of Pharmacology, University of Michigan, Ann Arbor, Michigan (R.R.N.); Institute de Recherches Internationales Servier, Neuilly sur Seine, France (M.S.); Systems Research, GlaxoSmithKline Research and Development, Research Triangle Park, North Carolina (T.K.); and Department of Pharmacology, University of Melbourne, Parkville, Australia (A.C.)

Abstract


I. Introduction

This update was undertaken to incorporate new information about multiple receptor conformational states and the recognition that multiple distinct agonist responses may result that have different pharmacological properties (Kenakin, 1995). Nomenclature concerning the actions of allosteric (allotopic) ligands is presented based on recent literature (Christopoulos and Kenakin, 2002). The implications of high receptor numbers in heterologous expression systems for interpretation of agonist function are discussed. Additional changes address the fact that many receptors are not single mac-
romolecules but are made up of multiple subunits. Finally, there are new recommendations regarding nomenclature for equilibrium constants.

II. Working Definition of a Receptor

A cellular macromolecule, or an assembly of macromolecules, that is concerned directly and specifically in chemical signaling between and within cells. Combination of a hormone, neurotransmitter, drug, or intracellular messenger with its receptor(s) initiates a change in cell function. Thus NC-IUPHAR does not classify simple binding sites, without function (although truncated proteins without signaling function may be designated as such, to avoid confusion). Furthermore, a receptor may consist of several proteins, called subunits. In some cases the large number of combinatorial possibilities for assembly of multiple subunits may require NC-IUPHAR to use an interim nomenclature based on the individual subunits (Spedding et al., 2002). Nevertheless, the ultimate goal is to define the multi-subunit assemblies that occur in vivo.

The regions of the receptor macromolecule to which ligands bind are referred to collectively as the recognition site(s) of the receptor. Those at which the endogenous agonist binds are termed primary or orthosteric sites whereas other ligands may act through allosteric sites (see Table 1).

III. Use of Drugs in Definition of Receptors or of Signaling Pathways

When using drugs to define receptors or signaling pathways, it would be desirable to use a drug that acts only on the receptor or biological site of interest at all concentrations and doesn’t interact with others at any achievable concentration. Unfortunately, there are very few or no drugs with this ideal property. Fortunately, there are numerous drugs with a detectable potency difference (in exceptional cases >10^3-fold but usually much less) between their primary target and other related receptors. Because these differences are not absolute, claims for the involvement of a particular receptor, or signaling protein, based on the use of such agents should be backed up by testing with multiple agents, and wherever possible, full concentration-response curves should be obtained for the definition of responses in in vitro experiments. Full dose-response curves should also be obtained in in vivo experiments, if ethical considerations allow.

A. The Expression of Amount of Drug: Concentration and Dose

1. Concentration. It is recommended that the molar concentration of substance X be denoted by either [X] or c_x, with the former preferred. Decimal multipliers should be indicated by the use of either Le Système International d’Unités (International System of Units) prefixes (e.g., μM, nM) or by powers of ten (e.g., 3 × 10^-8 M), with the former preferred.

2. Dose. In some circumstances (e.g., in therapeutics and clinical pharmacology, in in vivo experiments, and when tissues are perfused in vitro and exposed to a bolus application of drug), absolute drug concentrations are uncertain, and it becomes more appropriate to specify the quantity of drug administered. This may be done in terms of either mass or molar quantity. Units and routes of administration should be specified. In the case of in vivo experiments with animals, the quantity of drug is to be expressed per unit of animal mass (e.g., mol/kg, mg/kg). In therapeutics, milligrams per kilogram will normally be appropriate. Negative indices should be used where confusion otherwise arises (e.g., mg min^-1 kg^-1).

B. General Terms Used to Describe Drug Action

Table 1.

C. Experimental Measures of Drug Action

1. General Measures. Table 2.

2. Agonists. Table 3.

3. Antagonists. Table 4.

D. Terms and Procedures Used in the Analysis of Drug Action

1. The Quantification of Ligand-Receptor Interactions. Table 5.


3. Action of Antagonists. Table 7.

IV. Appendix

A. Microscopic and Macroscopic Equilibrium Constants

Microscopic and macroscopic equilibrium constants should be distinguished when describing complex equilibria, which occur with all agonists. The latter refers to a single constant describing the overall equilibrium (i.e., the value that would be obtained in a ligand binding experiment), whereas the former refers to each individual constant that describes each reaction step within the equilibrium. For the scheme

\[ \frac{K_1}{K_2} \]

the macroscopic equilibrium dissociation constant (denoted here as \( K_{\text{app}} \) for “K\text{apparent}”) is given by

\[ K_{\text{app}} = \frac{K_1K_2}{1 + K_2} \]

Here \( K_1 \) and \( K_2 \) are the microscopic equilibrium constants for the first and second reactions, respectively. Note that in this scheme, saturation radioligand binding assays and Furchgott’s (1966) irreversible antagonist method for determining the equilibrium dissociation
constant for an agonist would each provide an estimate of $K_{app}$ rather than $K_1$.

This distinction is also important when considering those receptors (e.g., ligand-gated ion channels) that have more than one binding site for the agonist.

**B. Schild Equation and Plot—Further Detail**

The Schild equation is based on the assumptions that (a) agonist and antagonist combine with the receptor macromolecule in a freely reversible but mutually exclusive manner, (b) equilibrium has been reached and that
### Experimental measures of drug action: general

<table>
<thead>
<tr>
<th>Term</th>
<th>Suggested Usage</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>The relationship between concentration and effect:</td>
<td>In the following, drug action is expressed in terms of the effect, ( E ), produced when an agonist, ( A ), is applied at a concentration ([A]). The relationship between ( E ) and ([A]) can often be described empirically by the Hill equation, which has the form:</td>
<td>([A]) in the Hill equation is sometimes denoted by ( K ), and ( E_{\text{max}} ) by ( a ). The choice between ([A]) and ( K ) will depend on the directness of the measurement. The former is appropriate if an indirect action, such as the contraction of an intact smooth muscle preparation, is observed. However, in a ligand binding experiment, ( K ) would be preferable, although whether the value of ( K ) corresponds to a single, microscopic, equilibrium dissociation constant (even if ( n_1 ) is unity) will depend on the circumstances (see Section IV. A.). The Hill equation and the logistic equation are closely related but not identical (see Section IV. C.).</td>
</tr>
<tr>
<td>Hill equation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potency</td>
<td>An expression of the activity of a drug, in terms of the concentration or amount needed to produce a defined effect; an imprecise term that should always be further defined (see ( EC_{50} ), ( IC_{50} ), etc.).</td>
<td>Drug potency depends on both receptor (affinity, efficacy) and tissue (receptor numbers, drug accessibility) parameters. The term is sometimes, incorrectly, used to refer to the maximum effect attainable.</td>
</tr>
</tbody>
</table>

### Experimental measures of drug action: agonists

<table>
<thead>
<tr>
<th>Term</th>
<th>Suggested Usage</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>( EC_{50} ) or ([A]_{50})</td>
<td>The molar concentration of an agonist that produces 50% of the maximal possible effect of that agonist. Other percentage values (( EC_{20}, EC_{40} ), etc.) can be specified. The action of the agonist may be stimulatory or inhibitory.</td>
<td>The mass concentration (g/l) should be used if the molecular weight of the test substance is unknown. It may sometimes be preferable to express the activity of a drug in terms of the concentration that causes a specified change in a baseline measurement (e.g., a 20 mm Hg change in perfusion pressure; a 30% increase in a muscle twitch). If the ( EC_{50} ) or ([A]<em>{50}) terminology is to be used in this context, the appropriate units must be included (e.g., ( EC</em>{50\text{mm}} ) or ([A]<em>{50\text{mm}})) to avoid confusion with ( EC</em>{50} ) or ([A]<em>{50}) as here defined. Because the relation between receptor occupancy and response is usually nonlinear, the ( EC</em>{50} ) generally does not directly measure the equilibrium dissociation constant of the agonist and therefore is only a descriptive term. The term ( ED_{50} ) is sometimes used interchangeably with ( EC_{50} ), but the former term is best reserved for in vivo use where actual doses, as opposed to concentrations, are used.</td>
</tr>
<tr>
<td>( ED_{50} )</td>
<td>Either the dose of a drug that produces, on average, a specified all-or-none response in 50% of a test population or, if the response is graded, the dose that produces 50% of the maximal response to that drug.</td>
<td>Units (e.g., mg/kg, mmol/kg or mg/l, mmol/l when a tissue is perfused) to be given. Applicable to in vivo measurements and to those in vitro experiments (e.g., with a perfused tissue) in which absolute concentration is uncertain. Otherwise use ( EC_{50} ). In some circumstances, the maximum response will be unknown. This will often be so in clinical pharmacology, for considerations of safety. The ( ED ) terminology is to be used for such measurements, the appropriate units must be included (e.g., ( ED_{50\text{mm}} ) or ([A]<em>{50\text{mm}})) to avoid confusion with ( EC</em>{50} ) or ([A]_{50}) as here defined.</td>
</tr>
<tr>
<td>( pEC_{50} ) or ( p[A]_{50})</td>
<td>The negative logarithm to base 10 of the ( EC_{50} ) of an agonist.</td>
<td>The term ( pEC_{50} ) has also been used, particularly in the earlier literature.</td>
</tr>
<tr>
<td>Maximal agonist effect</td>
<td>The maximal effect that an agonist, whether conventional or inverse, can elicit in a given tissue under particular experimental conditions. It is best expressed as a fraction of the effect produced by a full agonist of the same type acting through the same receptors under the same conditions.</td>
<td>Also referred to historically as intrinsic activity and designated as ( a ). The generic term maximal agonist effect is preferred because maximal effects are highly dependent on the experimental conditions such as tissue used, level of receptor expression, the type of measurement used (e.g., ( IP_{3} ), vs. ( Ca^{2+} ), vs. contraction or secretion), and changes in signal transduction efficiency. Thus intrinsic activity should not be used as a primary pharmacologic characteristic of an agonist as it is not a constant. A simple description of “maximal effect in (specified) assay” is preferred.</td>
</tr>
<tr>
<td>EMR</td>
<td>Equi-effective molar concentration ratio; the ratio of the molar concentrations of test and reference substances that produce the same biological effect (whether activation or inhibition).</td>
<td>Should be specified only if the log concentration-effect curves for the substances being compared are parallel.</td>
</tr>
<tr>
<td>EDR</td>
<td>Equi-effective dose ratio, as above, but used when doses rather than concentrations are compared, as in vivo work.</td>
<td></td>
</tr>
</tbody>
</table>

*EMR, equi-effective molar concentration ratio; EDR, equi-effective dose ratio.*
The ratio of the concentration of an agonist that produces a specified response (often but not necessarily 50% of the maximal response to that agonist in an assay) in the presence of an antagonist, to the agonist concentration that produces the same response in the absence of antagonist.

IC\textsubscript{50}

This term is used in a number of ways: (i) the molar concentration of an antagonist that reduces the response to an agonist by 50%; the concentration of agonist should be given; (ii) the molar concentration of an unlabeled agonist or antagonist that inhibits the binding of a radioligand by 50%; the concentration of radioligand should be given; (iii) the molar concentration of an inhibitory agonist that reduces a response by 50% of the maximal inhibition that can be attained; this latter usage is not recommended—instead the term, EC\textsubscript{50}, should be used since this is an agonist effect.

pA\textsubscript{2}

The negative logarithm to base 10 of the molar concentration of an antagonist that makes it necessary to double the concentration of the agonist needed to elicit the original submaximal response obtained in the absence of antagonist (Schild, 1947, 1949).

The law of mass action can be applied, (c) a particular level of response is associated with a unique degree of occupancy or activation of the receptors by the agonist, (d) the response observed is mediated by a uniform population of receptors, and (e) the antagonist has no other relevant actions, e.g., on the relationship between receptor and response. Under these circumstances, the slope of the Schild plot should be 1 and the resulting estimate of the pA\textsubscript{2} should be equal to the pK (negative logarithm of the antagonist equilibrium dissociation constant).

For an antagonist to be classified as reversible and competitive on the basis of experiments in which a biological response is measured, the following criteria must hold:

1. In the presence of the antagonist, the log agonist concentration-effect curve should be shifted to the right in a parallel fashion.
2. The relationship between the extent of the shift (as measured by the concentration ratio) and the concentration of the antagonist should follow the Schild equation over as wide a range of antagonist concentrations as practicable. Usually, the data are presented in the form of the Schild plot, and adherence to the Schild equation is judged by the finding of a linear plot with unit slope (see Note 2 below). Nonlinearity and slopes other than unity can result from many causes. For example, a slope greater than 1 may reflect incomplete equilibration with the antagonist or depletion of a potent antagonist from the medium, as a consequence either of binding to receptors or to other structures. A slope that is significantly less than 1 may indicate removal of agonist by a saturable uptake process, or it may arise because the agonist is acting at more than one receptor (the Schild plot may then be nonlinear). See Kenakin (1997) for a detailed account.

Note 1: The finding that the Schild equation is obeyed over a wide range of concentrations does not prove that the agonist and antagonist act at the same site. All that may be concluded is that the results are in keeping with the hypothesis of mutually exclusive binding, which may of course result from competition for the same site but can also arise in other ways (see Allosteric Modulators in Table 1 and Competitive Antagonism in Table 7).

Note 2: Traditional Schild analysis is based on the use of linear regression. Nowadays, with the almost ubiquitous availability of computers in most research environments, a more accurate approach to performing Schild analysis is to use computerized nonlinear regression to directly fit agonist/antagonist concentration-response data to the Gaddum/Schild equations. The advantages of this approach over traditional Schild analysis are described elsewhere (Waud, 1975; Black et al., 1985; Lew and Angus, 1995). One simple
TABLE 5  
Terms and procedures used in the analysis of drug action: the quantification of ligand-receptor interactions

<table>
<thead>
<tr>
<th>Term</th>
<th>Suggested Usage</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Concentration” of receptors</td>
<td>(</td>
<td>R</td>
</tr>
<tr>
<td>Number of receptors, (N)</td>
<td>The total number of receptors, expressed in terms of unit area of membrane, or per cell, or per unit mass of protein.</td>
<td></td>
</tr>
<tr>
<td>Proportion of receptors in specified states</td>
<td>(p_{LR}) for proportion (fraction) of receptors or binding sites free of ligand. (p_{LR}^{<em>}) for the proportion of receptors or binding sites occupied by the ligand (L). If a distinction is made between inactive and active states of the receptor, then (p_{LR}) refers to the inactive state, (p_{LR}^{</em>}) for the proportion of receptors in which (L) occupies its binding site(s) and which are in an active state. (p_{LR}) for the proportion of receptors in which (L) occupies its binding site(s) and which are in a distinct ((R')) state that differs from both the inactive and the fully active states. This may exhibit some classical signaling activity or it may differ from (R) or (R^{*}) in another property such as activation of different effectors, rates of internalization, or cellular trafficking (Berg et al, 1998; Kenakin and Onaran, 2002).</td>
<td></td>
</tr>
<tr>
<td>Rate constants for the binding of a ligand</td>
<td>(k_{-1}) for the association (forward) rate constant, and (k_{-1}^{*}) for the dissociation (backward) rate constant, in the reaction (L + R \rightleftharpoons LR)</td>
<td>Units to be specified ((\text{M}^{-1} \text{s}^{-1} \text{ or } \text{M}^{-1} \text{ min}^{-1})) for (k_{-1}), (\text{s}^{-1}) or (\text{min}^{-1}) for (k_{-1}^{<em>}) in the scheme illustrated. Lowercase symbols to be used to denote rate constants (cf., uppercase for equilibrium constants). Where there are several ligands, alphabetical subscripts can be added: e.g., (k_{-1A}, k_{-1B}). For more complicated schemes involving several reactions, subscripts 2, 3, etc., can be used: e.g., (L + R_{\text{im}} \rightleftharpoons LR_{\text{im}}^{</em>}).</td>
</tr>
<tr>
<td>Equilibrium dissociation constant for ligand-receptor interactions, (K)</td>
<td>In the simple scheme below, (K) is numerically equal to the ratio of dissociation to association rate constants (k_{-1}/k_{1}), and has the dimension (\text{M} (\text{mol/l})).</td>
<td>(K) can be used in combination with subscripts for clarity. Lowercase letter subscripts are used to designate the type of experimental approach used to determine the constant (e.g., (K_{a}, K_{b}); (K_{a}, K_{b})—see below) and uppercase letter subscripts designate the compound to which the constant refers (e.g., (K_{AX}, K_{BN}, K_{AXB}, K_{ABB}), for compounds (A) and (B), respectively). The choice of lowercase subscript that is used in combination with (K) is based on the following conventions:</td>
</tr>
<tr>
<td></td>
<td>(L + R \rightleftharpoons LR)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(k_{1})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(k_{-1})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(k_{1})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(k_{-1})</td>
<td></td>
</tr>
</tbody>
</table>

Note: The reciprocal of the equilibrium dissociation constant (the equilibrium association constant or affinity constant, in units of \(\text{M}^{-1}\)) can also be used, although this is not preferred.

Continued.
TABLE 5—Continued
Terms and procedures used in the analysis of drug action: the quantification of ligand-receptor interactions

<table>
<thead>
<tr>
<th>Term</th>
<th>Suggested Usage</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>pK</td>
<td>The negative logarithm to base 10 of the equilibrium dissociation constant, $K$ in molar concentration units. The term can be used in combination with subscripts as described above for equilibrium dissociation constants ($pK_a$, $pK_b$, $pK_i$, etc.).</td>
<td>There are two major benefits to using the $pK$ measures of pharmacological potency rather than the equilibrium constant $K$ itself. Since pharmacological potency often ranges over many orders of magnitude ($K$ values from $10^{-10}$ M to $&gt;10^{-3}$ M), it is easier to present and discuss these differences in a $pK$ form (i.e., values generally range from about 10 to 3). More importantly from a statistical point of view, concentration parameters are generally distributed in a log normal manner (Christopoulos, 1998) so standard deviations are symmetrical for $pK$ values but not for $K$ values.</td>
</tr>
</tbody>
</table>

Hill-Langmuir equation

$p_{LR} = \frac{[L]}{[L] + K}$ in which $p_{LR}$ is the fraction (proportion) of binding sites occupied by a ligand $L$ at equilibrium. It is assumed that the interaction between $L$ and the sites obeys the law of mass action and can be described by the simple scheme

$L + K \rightarrow K_{LR}$

in which $K$ is the equilibrium dissociation constant.

* The original usage of $K_b$ by Gaddum represented the binding constant of ligand $B$ to distinguish it from that of ligand $A$. More recent usage of $K_A$ or $pK_A$ usually refers to values derived from pharmacological blocking experiments. Thus, to maintain consistency with the use of lower case subscripts for inhibition and direct binding experiments (i.e., $K_i$ and $K_a$) we recommend using $K_b$ or $pK_b$ for estimates of the dissociation constant that are derived from pharmacological blocking experiments (e.g., Schild plots).

TABLE 6
Terms and procedures used in the analysis of drug action: agonists

<table>
<thead>
<tr>
<th>Term</th>
<th>Suggested Usage</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desensitization, fade, tachyphylaxis</td>
<td>Overlapping terms that refer to a spontaneous decline in the response to a continuous application of agonist, or to repeated applications or doses. The following usages are suggested: fade, the waning of a response in the continued presence of agonist; tachyphylaxis, a decline in the response to repeated applications or doses of agonist. No mechanism is implied by either term. It is recommended that desensitization be used when the fade or tachyphylaxis is considered to be a direct consequence of receptor activation.</td>
<td>In Stephenson’s formulation (1956), combination of an agonist with its receptors is considered to result in a signal or “stimulus” $S$, which is equated to the product of the efficacy of the agonist $A$ and the proportion of receptors occupied: $S_A = \epsilon A_{ARB}$. When the response of a tissue is half-maximal, $S$ is assigned the value unity. Hence, a partial agonist that when occupying all the receptors produces a maximal response that is half that of a full agonist (under the same experimental conditions), has an efficacy of unity. Efficacy is both agonist- and tissue-dependent.</td>
</tr>
</tbody>
</table>

The expression *intrinsic efficacy*, $\epsilon$, was introduced by Furchgott (1966) to denote the notional efficacy associated with a single receptor: $\epsilon = [R_1]$ in which $[R_1]$ indicates the total concentration of receptors. This term is now also used in a wider sense (see below). Black and Leff (1983) provided another description of differences in the ability of agonists to produce a maximal effect. They defined the term $\tau$ (tau) as $[R_1]/K_{AB}$ in which $K_{AB}$ is the midpoint parameter of an explicit function relating receptor occupancy to the response of a tissue. Recent advances in the understanding of receptor function have identified the importance of distinguishing between the occupation of a receptor by an agonist and the activation of that receptor. This distinction was not considered in the earlier work. More detailed models of receptor action are therefore required, and these provide a better framework for expressing, and explaining, differences in the ability of agonists to activate receptors. The term *intrinsic efficacy* is now often used when discussing the agonist, rather than the tissue-dependent component of efficacy in such schemes (e.g., the isomerization model of del Castillo and Katz (1957), also Colquhoun (1987), the ternary model of DeLean et al. (1980), also Samama et al. (1990). However, Stephenson’s *efficacy*, and Black and Leff’s $\tau$, can still serve as useful comparative measures of the activity of agonists on intact tissues. |
method is to fit agonist EC$_{50}$ data, determined in the absence and presence of antagonist, to the following equation:

$$pEC_{50} = -\log([B]S + 10^{-pA2S}) - \log c$$

where pEC$_{50}$ and pA$_2$ are as defined previously in Tables 3 and 4, respectively, [B] denotes the antagonist concentration, S is a logistic slope factor analogous to the Schild slope and log c is a fitting constant (Motulsky and Christopoulos, 2003). This equation is based on a modification of the original Gaddum/Schild equations that results in more statistically reliable parameter estimates than those obtained using the original equations for nonlinear regression (Waud and
In competitive antagonism, the binding of agonist and antagonist is mutually exclusive. This may be because the agonist and antagonist compete for the same binding site or combine with adjacent sites that overlap (syntopic interaction). A third possibility is that different sites are involved but that they influence the receptor macromolecule in such a way that agonist and antagonist molecules cannot be bound at the same time.

If the agonist and antagonist form only short-lasting combinations with the receptor, so that equilibrium between agonist, antagonist, and receptors is reached during the presence of the agonist, the antagonism will be surmountable over a wide range of concentrations (reversible competitive antagonism). In contrast, some antagonists, when in close enough proximity to their binding site, may form a stable covalent bond with it (irreversible competitive antagonism), and the antagonism becomes insurmountable when no spare receptors remain.

More generally, the extent to which the action of a competitive antagonist can be overcome by increasing the concentration of agonist is determined by the relative concentrations of the two agents, by the association and dissociation rate constants for their binding, and by the duration of the exposure to each.

Current usage should be limited to the action of blockers on the same receptor (such as channel block of the nicotinic receptor). Prior use to describe the inhibition by adrenoceptor antagonists of the response to tyramine would be better termed indirect antagonism (Table 1).

The converse phenomenon surmountable antagonism is generally observed with reversible competitive antagonism though it may also occur with chemical antagonism, with irreversible antagonists in the case of spare receptors, or with certain forms of allosteric antagonism.

In disecting mechanisms of insurmountable antagonism, it is often helpful to distinguish between the locus of the action (competitive, noncompetitive, or indirect) and the kinetics of the action (reversible and irreversible). This can usually be done with appropriately designed time course or preincubation/blocking experiments.

Equating occupancies by an agonist first in the absence and then in the presence of a reversible competitive antagonist leads to the Schild equation (see below), and the terms Schild equation and Gaddum equation have sometimes been regarded as interchangeable.

The linearity and slope provide information about the nature of the antagonism. In practice, it is preferable to analyze agonist/antagonist interaction data by direct curve fitting to the Gaddum or Schild equations using computer-assisted nonlinear regression, but the Schild plot remains a useful graphical aid (see Section IV. B.).

In practice, it is difficult to distinguish syntopic orthosteric antagonism from very strong allosteric antagonism (i.e., allosteric antagonism that is characterized by very high negative cooperativity between the orthosteric site and the allosteric site).

### Table 7

<table>
<thead>
<tr>
<th>Term</th>
<th>Suggested Usage</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Competitive antagonism</td>
<td>In competitive antagonism, the binding of agonist and antagonist is mutually exclusive. This may be because the agonist and antagonist compete for the same binding site or combine with adjacent sites that overlap (syntopic interaction). A third possibility is that different sites are involved but that they influence the receptor macromolecule in such a way that agonist and antagonist molecules cannot be bound at the same time.</td>
<td></td>
</tr>
<tr>
<td>Noncompetitive antagonism</td>
<td>Agonist and antagonist can be bound to the receptor simultaneously; antagonist binding reduces or prevents the action of the agonist with or without any effect on the binding of the agonist.</td>
<td></td>
</tr>
<tr>
<td>Insurmountable antagonism</td>
<td>A descriptive term indicating that the maximum effect of the agonist is reduced by either pretreatment or simultaneous treatment with the antagonist. This can encompass several distinct molecular mechanisms such as: (a) irreversible competitive antagonism; (b) noncompetitive antagonism; and (c) functional antagonism (see Table 1). The converse phenomenon surmountable antagonism is generally observed with reversible competitive antagonism though it may also occur with chemical antagonism, with irreversible antagonists in the case of spare receptors, or with certain forms of allosteric antagonism.</td>
<td></td>
</tr>
<tr>
<td>Gaddum equation</td>
<td>$p_{AB} = \left( \frac{[A]}{[A] + K_A \left( 1 - \frac{[B]}{K_B} \right)} \right)$</td>
<td></td>
</tr>
<tr>
<td>The Schild equation</td>
<td>$r - 1 = \frac{[B]}{K_B}$</td>
<td></td>
</tr>
<tr>
<td>The Schild plot</td>
<td>A graph of $\log (r - 1)$ against log antagonist concentration, where $r$ is the concentration ratio (see Table 4). This should yield a straight line of unit slope if the Schild equation is obeyed (Arunlakshana and Schild, 1959).</td>
<td></td>
</tr>
</tbody>
</table>

The relationship (Gaddum, 1937, 1943) that replaces the Hill-Langmuir equation (see Table 5) when two ligands, $A$ and $B$, are in equilibrium with a common binding site. $p_{AB}$ is the proportion of the binding sites occupied by $A$, $K_A$ and $K_B$ are the equilibrium dissociation constants of $A$ and $B$, respectively.
et al., 1978; Lazareno and Birdsall, 1993). If \( S \) is not significantly different from 1, then it should be constrained as such and the equation re-fitted to the data.

C. The Relationship between the Hill and Logistic Equation

The logistic function is defined by the equation

\[
y = \frac{1}{1 + e^{-a x + b}}
\]

where \( a \) and \( b \) are constants. If \( a \) is redefined as \(-\log_e(K_b)\), and \( x \) as \( \log_e z \), then

\[
y = \frac{z^b}{K^b + z^b}
\]

which has the same form as the Hill equation.

Acknowledgments. We acknowledge helpful comments from Tom Bonner, Steven Foord, Steve Watson, and Sir James Black.

References


Cheng Y and Prusoff W (1973) Relationship between the inhibition constant (K) and the concentration of inhibitor which causes 50 per cent inhibition (I50) of an enzymatic reaction. Biochem Pharmacol 22:3099–3108.


