

<p>Slide 1</p>	<h1 style="text-align: center;">Disease Progress</h1> <p style="text-align: center;">Nick Holford Dept Pharmacology and Clinical Pharmacology University of Auckland</p>	
<p>Slide 2</p>	<h2 style="text-align: center;">Outline</h2> <ol style="list-style-type: none"> 1. What is disease progress? 2. Models for disease progress 3. Models for drug action 4. Placebo effects 5. Practical Example <p style="font-size: small;">©NHG Holford, 2012, all rights reserved.</p>	<p>Disease progression describes the natural history of disease without treatment. The word 'progression' implies a direction of change – usually with worsening severity.</p> <p>Disease progress refers to a description of disease progression plus changes attributable to treatments and placebo responses.</p>
<p>Slide 3</p>	<h2 style="text-align: center;">Clinical Pharmacology</h2> <p style="text-align: center;">=</p> <h2 style="text-align: center;">Disease Progression + Drug Action</h2> <p style="font-size: small;">©NHG Holford, 2012, all rights reserved.</p>	<p>Clinical pharmacology can be described as the science of understanding disease progress which is the result of disease progression (clinical) and drug action (pharmacology).</p> <p>Disease progression implies that the disease changes with time.</p> <p>Drug action refers to the time course of drug effect and includes pharmacokinetics, pharmacodynamics and a link model to account for delays in effect in relation to drug concentration.</p> <p>Clinical pharmacology is not a static description of the use of a drug but includes the time course of disease, drug concentration and drug effect.</p>

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Old Model - New Meaning

$$E = E0 + \frac{E_{\max} \cdot Conc}{EC50 + Conc}$$

Disease Progression

Drug Action

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Early approaches (e.g. Holford & Sheiner 1981) describing the time course of drug effect distinguished a constant baseline response ($E0$) from a varying concentration related response (e.g. the E_{\max} model). The constant baseline parameter describes the response in the absence of drug and is the simplest form of disease progress model.

The use of the symbol $E0$ for the baseline response was not a good choice because the effect (E) when concentration is zero must be zero i.e. $E0$ is not the drug effect when concentration is zero but is the biological response (biomarker) that is being observed.

Holford NHG, Sheiner LB. Understanding the dose-effect relationship: clinical application of pharmacokinetic-pharmacodynamic models. Clin Pharmacokinet. 1981;6(6):429-53.

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Disease Progression Model

- **Quantitative model that accounts for the time course of disease status, $S(t)$:**

- **“clinical outcome”**

- **Survival** - Dead or alive (or had a stroke or not, etc.)
- **Symptoms** - measure of how a patient feels or functions

- **“biomarkers”**

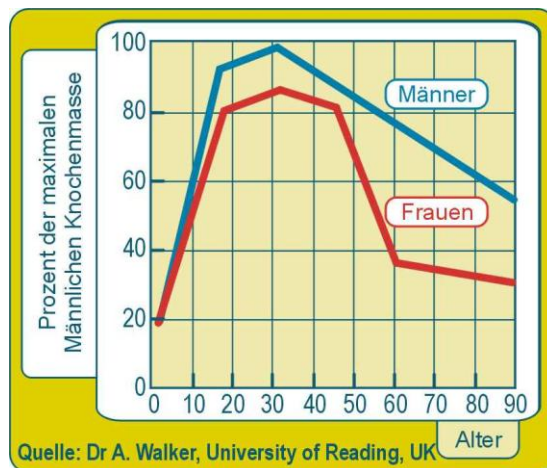
- **Signs** - physiological or biological measurements of disease activity

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A more appropriate symbol to describe disease progress is ‘ S ’ i.e. the disease status. Disease status is expected to vary with time, $S(t)$.

Disease status may be defined in terms of clinical outcomes such as survival and symptoms or in terms of a biomarker. Biomarkers are also known as clinical signs when used by clinicians as diagnostic or prognostic variables.

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A biomarker description of disease progression.

Bone mineral density (Knochenmasse) measured in men (Männer) and women (Frauen) is shown over ages (Alter) ranging from 0 to 90. Most therapeutic studies on bone mineral density (BMD) cover less than 10 years so there is a limited understanding of drug effects on disease progression. Note that this figure suggests that the rate of loss of BMD slows in older women – as it must because BMD cannot go negative.

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The Link Between Biomarkers and Outcome Is Well Known



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Components of a Disease Progress Model

- Baseline Disease State
- Natural History
- Active Treatment Response
- Placebo Response

$$S(t) = S_0 + \text{Nat. Hx.} + \text{Active} + \text{Plac}$$

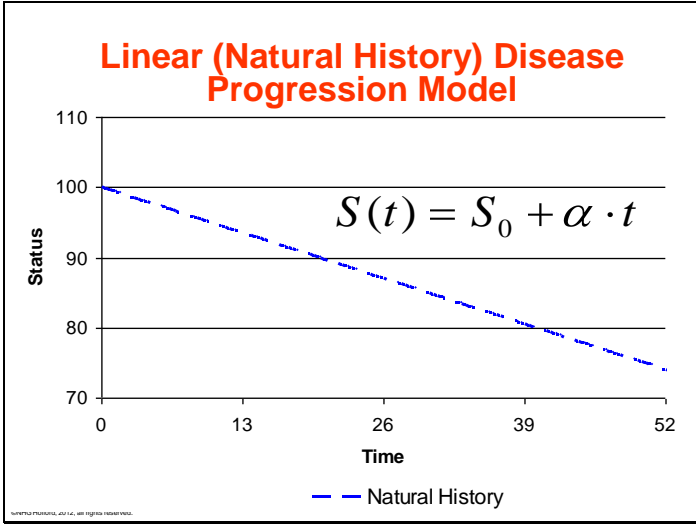
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Disease progress models start with a baseline disease status, S_0 . The change from baseline in the absence of drug treatment describes the natural history of the disease (disease progression). When drugs are used then the active effect of the drug modifies disease status. In clinical trials it is also necessary to consider the placebo response as a separate component.

Some disease progress models are described in Holford NHG, Mould DR, Peck CC. Disease progress models. In: Atkinson A, editor. Principles of Clinical Pharmacology. 2nd ed. San Diego: Academic Press; 2007. p. 313-21.

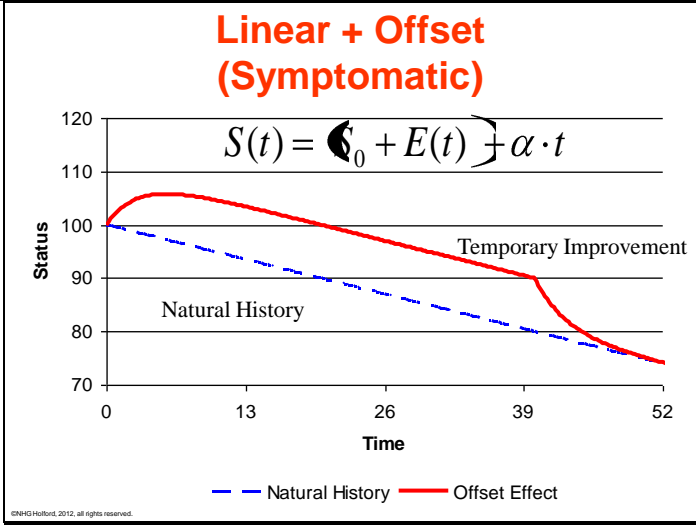
More complex effects based on turnover models have been described in Post TM, Freijer JI, DeJongh J, Danhof M. Disease system analysis: basic disease progression models in degenerative disease. Pharm Res. 2005 Jul;22(7):1038-49.

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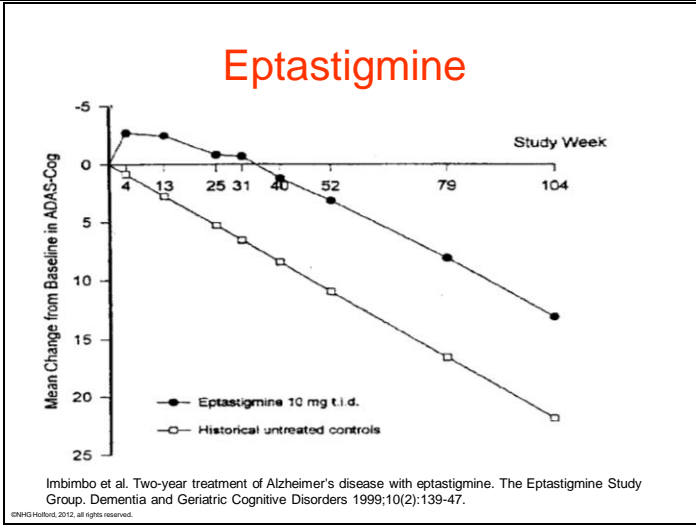
The simplest model to describe changing disease status with time is linear. In general if the change is relatively small in relation to the time scale of observation then any disease progress curve will reasonably be described by a linear function.

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With any disease progress model it is possible to imagine a drug action that is equivalent to a change in the baseline parameter of the model. This kind of effect on disease produces a temporary offset. When treatment is stopped the response to the drug washes out and the status returns to the baseline. In many cases it is reasonable to suppose that the processes governing a delay in onset of drug effect will also affect the loss of effect but the offset effects of levodopa treatment in Parkinson's disease are one exception to this assumption.

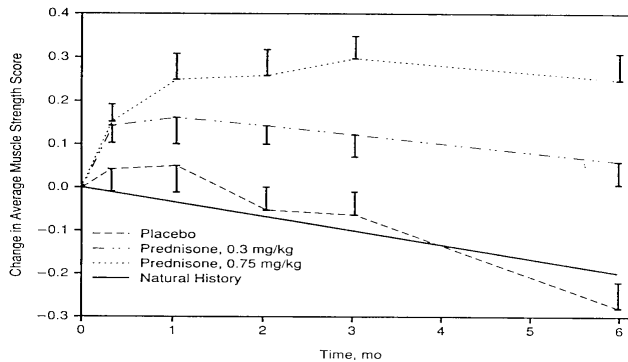
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The action of cholinesterase inhibitors in Alzheimer's disease is very similar for all drugs in this class. There is a delayed onset of benefit taking 2 to 3 months to reach its peak followed by continuing progression of the disease at the same rate as expected from natural history progression. This is clear example of an offset type of drug action. If there is a protective effect it is small and hard to detect without withdrawal of treatment.

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Linear + Offset + Placebo

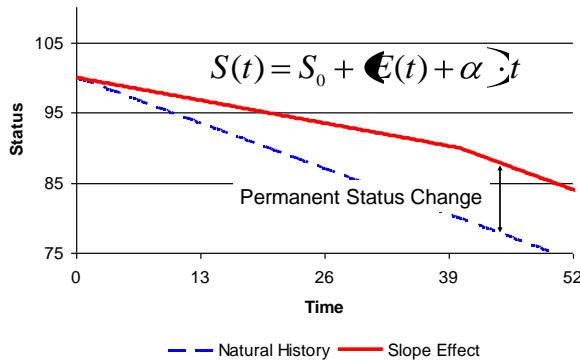


Griggs RC, Moxley RT, Mendell JR, Fenichel GM, Brooke MH, Pestronk A, et al. Prednisone in Duchenne Dystrophy: A randomized, controlled trial defining the time course and dose response. Archives of Neurology 1991;48:383-88
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Muscular dystrophy causes a progressive loss of muscle strength. This graph shows the author's belief that the natural history is essentially linear over 6 months. The effects of two doses of prednisone demonstrate a delayed onset of effect but no change in the rate of progression after the maximum effect is achieved. This seems to be an example of an offset type of drug effect. The response to placebo is also delayed but differs from prednisone by loss of effect and return to the natural history rate of progression. The difference in time course of drug action, placebo response and natural history components allows these three phenomena to be distinguished.

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Linear + Slope (Disease Modifying)

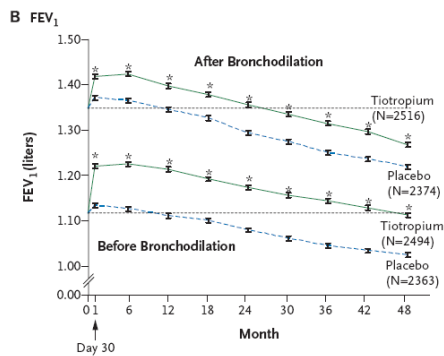


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Drug effects on the slope of a linear model lead to permanent changes in the disease status which are not reversed when treatment is stopped. The persistent change after stopping treatment is the hallmark of a disease modifying action if the natural history is linear.

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Symptomatic or Disease Modifying?



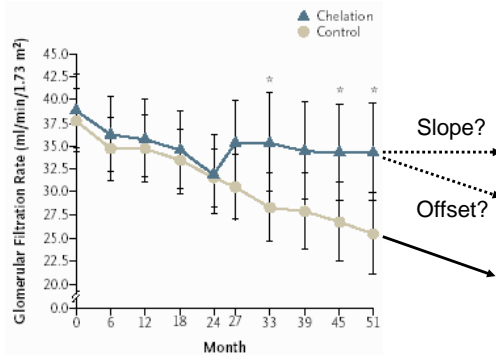
Tashkin DP, Celli B, Senn S, Burkhardt D, Kesten S, Menjoge S, et al. A 4-Year Trial of Tiotropium in Chronic Obstructive Pulmonary Disease. N Engl J Med. 2008;359(15):1543-54.

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The FEV₁ is a measure of airway resistance. Tiotropium is an inhaled anti-cholinergic bronchodilator. FEV₁ was measured before and after bronchodilation with inhaled salbutamol (albuterol). Patients with chronic obstructive pulmonary disease (COPD) treated with placebo or with tiotropium show an initial symptomatic response which appears to be maintained in the tiotropium treated group. There is no indication of a disease modifying effect. Before bronchodilation, the annual rates of decline were the same in the tiotropium group and the placebo group: 30±1 ml per year. After bronchodilation, the annual rate of decline was 40±1 ml per year in the tiotropium group, as compared with 42±1 ml per year in the placebo group. Results of this kind of trial looking for disease modifying effects are still controversial because of naive data analysis approaches that cannot distinguish symptomatic from disease modifying effects. Niewoehner DE. TORCH and UPLIFT: what has been learned from the COPD "mega-trials"? COPD. 2009;6(1):1-3.

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Symptomatic and Disease Modifying?



Lin J-L, Lin-Tan D-T, Kuang-Hong H, Chen-Chen Y. Environmental lead exposure and progression of chronic renal diseases in patients without diabetes. *New England Journal of Medicine* 2003;348(4):277-286

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A trial was undertaken in Taiwan in patients with moderate renal functional impairment. After 2 years of follow up they were randomized to treatment with a lead chelating agent. Patients who received chelation treatment had a rapid improvement in function which could be described by an offset effect. There was also a marked slowing of the rate of decline of renal function. This could be described by a slope effect but without washout of treatment it is not possible to distinguish a true disease modifying effect from a slow onset offset effect.

"64 subjects with an elevated body lead burden were randomly assigned to the chelation control groups. For three months, the patients in the chelation group received lead-chelation therapy with calcium disodium EDTA, and the control group received placebo. During the ensuing 24 months, repeated chelation therapy was administered weekly to 32 patients with high-normal body lead burdens (at least 80 µg but less than 600 µg) unless on repeated testing the body lead burden fell below 60 µg; the other 32 patients served as controls and received weekly placebo infusions for 5 weeks every 6 months."

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Parkinson Study Group DATATOP Cohort

Deprenyl and Tocopherol Antioxidative Therapy of Parkinsonism

PKPD of anti-parkinsonian treatment
and Parkinson's disease over 7 years
in 800 patients

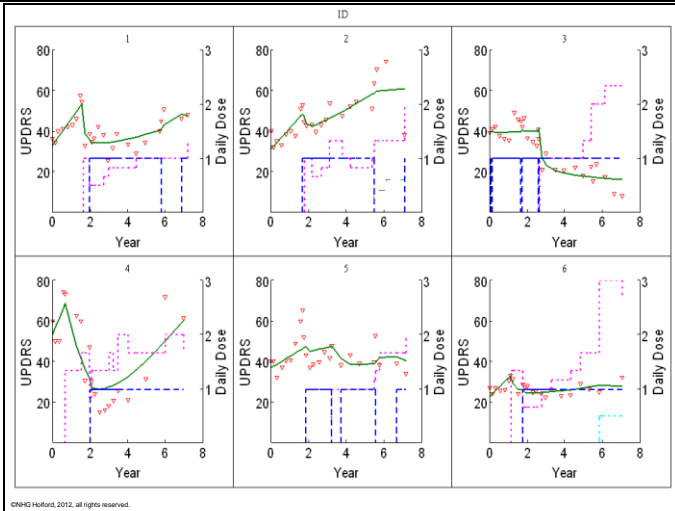
The Parkinson Study Group. Effect of deprenyl on the progression of disability in early Parkinson's disease. *The New England Journal of Medicine* 1989;321:1364-1371

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The DATATOP study was performed over 2 year period but patients enrolled in the study were subsequently followed up for 8 years. The time course of disease status in Parkinson's disease and the effects of treatment were described by a disease progress model. The NM-TRAN code for this analysis can be found in Holford et al. 2006.

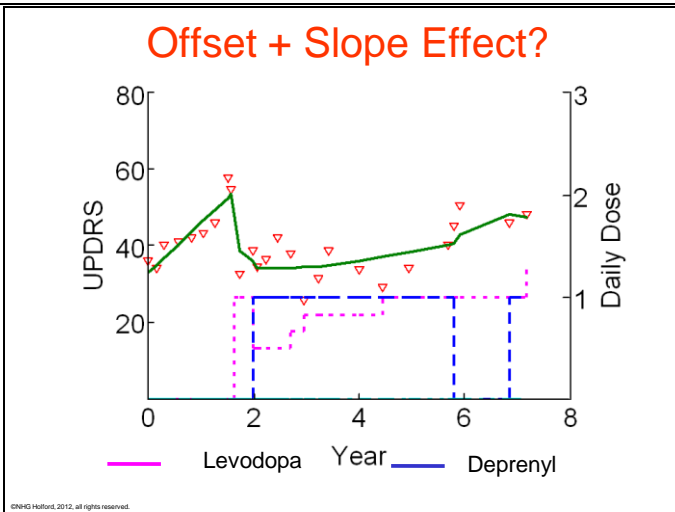
Holford NHG, Chan PL, Nutt JG, Kieburtz K, Shoulson I. Disease progression and pharmacodynamics in Parkinson disease - evidence for functional protection with levodopa and other treatments. *J Pharmacokinet Pharmacodyn.* 2006 Jun;33(3):281-311.

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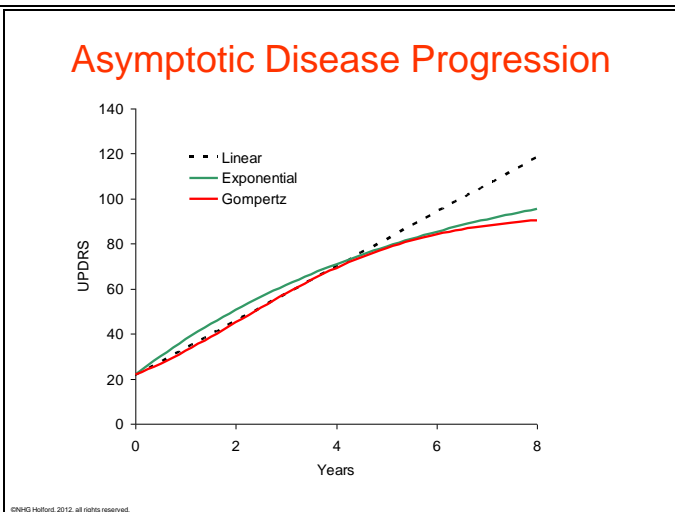
Disease status was followed with the Unified Parkinson's Disease Response Scale (UPDRS). The UPDRS patterns were quite variable from patient to patient. A major source of variability was the response to individual drug treatments.

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The first patient in the DATATOP cohort shows the patterns that were eventually used to build a disease progression and drug action model. The initial rate of progression seems to be slowed when treatment with levodopa and deprenyl is used. In addition there is a marked symptomatic effect which is primarily attributable to levodopa. It is not obvious what disease progression model is most suitable but it could be linear. Testing different model led to the conclusion that the disease progression approached an asymptote using a Gompertz model.

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The exponential asymptotic model has its fastest change at early times with continuously decreasing rate of change as the asymptote is reached. A sigmoidal shape with the maximum rate of change in the middle of the curve is obtained with a Gompertz function. The Gompertz function has a long history for describing survival time distributions and for tumour growth curves. The shapes of the linear, exponential asymptote and Gompertz asymptote are shown based on estimates obtained in patient's with Parkinson's disease. The initial dip in the Gompertz curve relative to the exponential curve could be due to a transient placebo response.

Asymptotic Disease Progression

Linear $\frac{dS}{dt} = \alpha \cdot f(Ce)$

Exponential $\frac{dS}{dt} = \frac{\ln(2)}{T_{prog}} \cdot (S_{ss} \cdot f(Ce) - S)$

Gompertz $\frac{dS}{dt} = \frac{1}{T_{prog} \cdot f(Ce)} \cdot (S_{ss} - S) \cdot S$

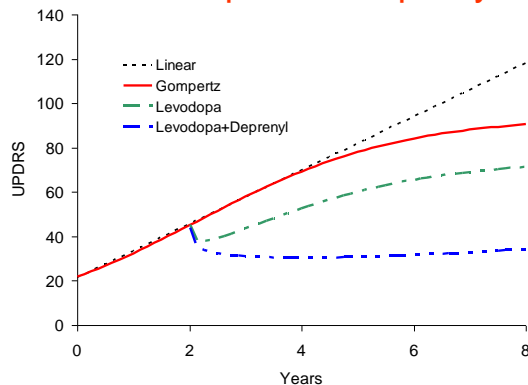
α = Linear progression rate
 T_{prog} = Progression half-life (exponential) or time constant (Gompertz)
 S_{ss} = Asymptotic 'burnt out' steady state

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Each parameter in a disease progress model represents a possible site of action for a drug. All models have a baseline parameter which can be thought of as the basis for a symptomatic drug effect. A linear model has as slope parameter which is the basis for a disease modifying drug effect. Asymptotic disease progress models may have two parameters – an asymptote representing the eventual steady state for the disease and a time related parameter determining the time to the asymptote. Drug effects on either of these parameters can lead to a disease modifying effect.

Note that the T_{prog} parameter for the exponential model is the half-life of progression to the asymptote. But the T_{prog} parameter for the Gompertz model is a second order time constant. Interpretation of its value has to refer to the disease status e.g. if T_{prog} is 20 years and the disease status has a value of 10 then progression at that status has a time constant of 2 years ($T_{prog}/status$). If the status is chosen at the mid point between S_0 and S_{ss} it corresponds to the status expected after one half-life with the exponential model. In that case a half-time of progression can be calculated e.g. if the mid-point status is 40 then the time constant is 0.5 and the equivalent half-life is $\ln(2) \cdot 0.5$ or 0.347.

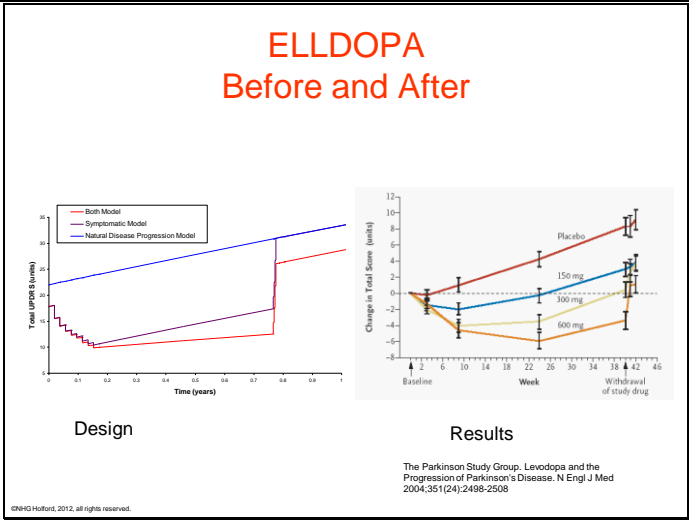
Offset and Disease Modifying Effects of Levodopa and Deprenyl



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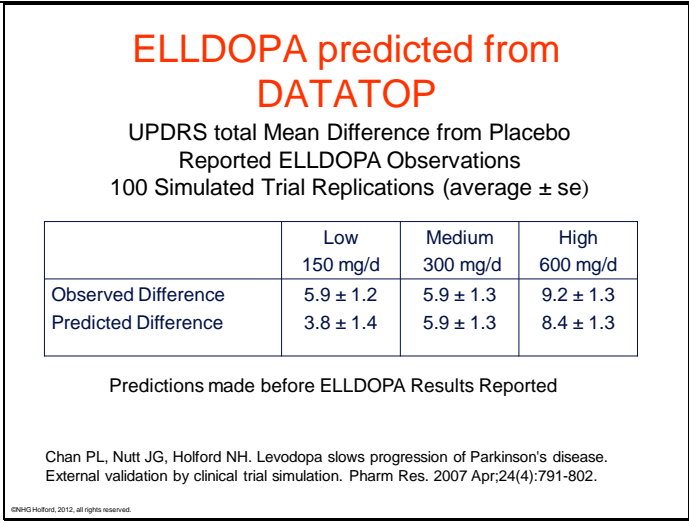
The effects of levodopa and deprenyl are shown. Both have offset effects and disease modifying effects which was described by an action on the time constant of a Gompertz asymptotic model. See Holford et al 2006 for details of the model code.

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The Parkinson Study Group which performed the DATATOP study was interested in asking if levodopa changes the rate of progression of Parkinson's disease. They designed a trial that was simple in principle but it rested on a key assumption that symptomatic effects of levodopa would wash out within 2 weeks of stopping treatment. When treatment was stopped after 9 months there was a loss of UPDRS response over the next 2 weeks but it did not approach the response seen in a parallel placebo treated group. The marked difference from placebo could be due to a true disease modifying effect or a very slow loss of symptomatic effect.

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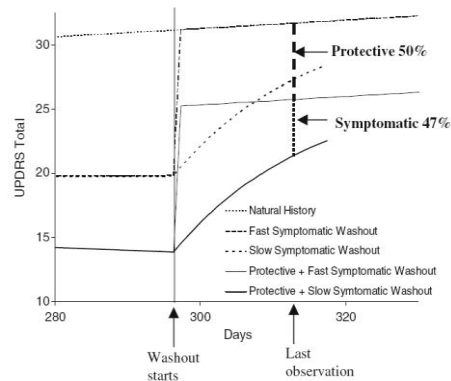
The ELLDOPA study was prospectively simulated using the model for disease progress and levodopa effects obtained from the DATATOP cohort. The predicted difference from placebo in three levodopa dose groups was very similar to the observed response. This is a form of external validation of the DATATOP model. This is a very strong test of the value of the model developed from DATATOP because it predicted the outcome of a trial with a very different design. It confirms the predictions of the DATATOP model in the short term (just over 9 months).

Chan PL, Nutt JG, Holford NH. Levodopa slows progression of Parkinson's disease. External validation by clinical trial simulation. Pharm Res. 2007 Apr;24(4):791-802.

Note: SEs for observed differences have been corrected. Published SEs in Chan et al. 2007 were incorrect.

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What Happened in ELLDOPA?



Using the parameters describing the washout of levodopa symptomatic effects obtained from a small group of patients originally in the DATATOP cohort (Hauser & Holford 2002) along with the disease progress and levodopa symptomatic and disease modifying effects it was possible to predict the symptomatic contribution to the observed difference from placebo after 2 weeks of levodopa washout. This is an example of the utility of modelling both disease progress and drug action. Not only can trial results be predicted but also the results can be interpreted in a more meaningful way. The DATATOP model was used to explain how much of the effect observed after washout of levodopa could be attributed to residual symptomatic effects (47%) compared to the disease modifying effect (50%). The sum of the effects does not add to 100% because the numbers are derived from stochastic simulations for each fast and slow symptomatic washout curves. Hauser RA, Holford NHG. Quantitative description of loss of clinical benefit following withdrawal of levodopa-carbidopa and bromocriptine in early Parkinson's disease. *Mov Disord.* 2002;17(5):961-8.

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Disease Progress Models

- **Alzheimer's Disease**
 - Progress: Linear
 - Action: Offset
- **Parkinson's Disease**
 - Progress: Non-Linear
 - Action: Offset and Disease Modifying
- **Other Diseases**
 - e.g. COPD, diabetes, hypertension
 - Does treatment modify progression?

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The time course of biomarkers in Alzheimer's disease and Parkinson's disease has been used to identify the shape of the natural history curve for the biomarker. Drug actions can also be identified. Disease modifying effects of treatment in other major diseases are still under debate.

<p>Slide 26</p>	<h2 style="text-align: center; color: red;">General References</h2> <ol style="list-style-type: none"> 1. Chan PLS, Holford NHG. Drug treatment effects on disease progression. <i>Annu Rev Pharmacol Toxicol.</i> 2001;41:625-59. 2. Holford NHG, Mould DR, Peck CC. Disease Progress Models. In: Atkinson A, editor. <i>Principles of Clinical Pharmacology.</i> San Diego: Academic Press; 2001. p. 253-62. 3. Post TM, Freijer JI, DeJongh J, Danhof M. Disease system analysis: basic disease progression models in degenerative disease. <i>Pharm Res.</i> 2005 Jul;22(7):1038-49. 4. Ploeger BA, Holford NH. Washout and delayed start designs for identifying disease modifying effects in slowly progressive diseases using disease progression analysis. <i>Pharm Stat.</i> 2009 Jul-Sep;8(3):225-38. <p style="font-size: small;">©NHG Holford, 2012, all rights reserved.</p>	
<p>Slide 27</p>	<h2 style="text-align: center; color: red;">Offset Model Code</h2> <pre> \$ERROR CE=F ; Immediate Effect PK S0=THETA (1) *EXP (ETA (1)) ALPHA=THETA (2) * (1+ETA (2)) ; Note proportional ETA BETA=THETA (3) * (1+ETA (3)) ;Offset Drug Action Y=S0 + ALPHA*TIME + BETA*CE + EPS (1) </pre> <p style="font-size: small;">©NHG Holford, 2012, all rights reserved.</p>	<p>This code assumes that the drug action is described by a PK model for concentration which has an immediate effect. Any PK model can be used and a delayed effect could be modelled by using an effect compartment model.</p> <p>The drug action is added to the baseline (S0) in order to produce an offset effect. Note that the rate of progression of disease (alpha) and the effect of the drug (beta) may be either positive or negative in an individual patient. It is important not to use an exponential model for the random effects so that both patterns of progress and drug action can be described.</p>
<p>Slide 28</p>	<h2 style="text-align: center; color: red;">Placebo Model Code</h2> <pre> \$ERROR CE=F ; Immediate Effect PK S0=THETA (1) *EXP (ETA (1)) ALPHA=THETA (2) * (1+ETA (2)) BETA=THETA (3) * (1+ETA (3)) ;Single Placebo 'dose' DOSEP=THETA (4) *EXP (ETA (4)) TELP=THETA (5) *EXP (ETA (5)) TEQP=THETA (6) *EXP (ETA (6)) ;First Order input and elimination 'Bateman' function KELP=LOG(2)/TELP ; placebo 'elimination' KEQP=LOG(2)/TEQP ; placebo 'absorption' TWOEXP=EXP (-KELP*TIME) -EXP (-KEQP*TIME) PLACBO=DOSEP*KEQP/(KEQP-KELP) *TWOEXP Y=S0 + ALPHA*TIME + BETA*CE + PLACBO + EPS (1) </pre> <p style="font-size: small;">©NHG Holford, 2012, all rights reserved.</p>	<p>It is reasonable to suppose that the start of a clinical trial is the stimulus for the placebo response. The placebo response can be imagined to be due to the time course of placebo 'concentration' after a placebo 'dose' at time zero (the start of the trial). A basic pharmacokinetic first order absorption and elimination model can be used to describe the placebo time course.</p> <p>Differences in height of response between patients are determined by the apparent placebo 'dose'. Differences in the rate of appearance and loss of response are determined by the 'absorption' and 'elimination' half-lives. This type of placebo model function has been used to describe the placebo response in Alzheimer disease trials.</p> <p>Holford NHG, Peace KE. Methodologic aspects of a population pharmacodynamic model for cognitive effects in Alzheimer patients treated with tacrine. <i>Proc Natl Acad Sci U S A.</i> 1992;89:11466-70.</p>

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Slope Effect Code

```
$PK
S0=THETA(1)*EXP(ETA(1))
ALPHA=THETA(2)*(1+ETA(2))
BETA=THETA(3)*(1+ETA(3))
CL=THETA(4)*EXP(ETA(4))
V=THETA(5)*EXP(ETA(5))

; Must use differential equations for SLOPE effect

$DES
CE=A(1)/V
DADT(1) = -CL*CE ; PK model
DADT(2) = BETA*CE + ALPHA ; Slope Action

$ERROR
DISPRG=A(2)
Y=S0 + DISPRG + EPS(1)
```

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Note that protective effect models must be coded as differential equations because drug concentration (CE) varies with time

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Asymptotic Progress Code

```
$PK
S0=THETA(1)*EXP(ETA(1)) ; baseline
SSS=THETA(2)*(1+ETA(2)) ; asymptote steady state status
DLTA= SSS - S0 ; change from baseline to asymptote
THALF=THETA(3)*EXP(ETA(3)) ; half-life of asymptotic process
BETA=THETA(4)*(1+ETA(4)) ; drug effect parameter
CL=THETA(5)*EXP(ETA(5)) ; PK model clearance
KPROG=LOG(2)/THALF

$DES
CE=A(1)
STATUS=A(2)
DADT(1) = -CL*CE ; PK model
DADT(2) = KPROG*(DLTA*(1+BETA*CE) - STATUS) ; exponential asymptote

$ERROR
DISPRG=A(2)
Y=S0 + DISPRG + EPS(1)
```

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The drug effect is shown as an action on the steady state asymptote (SSS). Alternatively it could have been on the exponential rate constant (Kprog) or on both SSS and Kprog.