Clinical Pharmacology can be described as the science of understanding disease progress (clinical) and drug action (pharmacology). Disease progress implies that the disease changes with time. 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. 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.

Outline

1. What is disease progress?
2. Models for disease progress and drug action
3. Parkinson’s disease and survival
4. Osteoporosis and fractures
Disease Progress Model

- Quantitative model that accounts for the time course of disease status, S(t):
  - "biomarkers"
    - Signs - physiological or biological measurements of disease activity
  - "clinical outcome"
    - Symptoms - measure of how a patient feels or functions
    - Survival - Dead or alive (or had a stroke or not, etc.)

A 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.
The Link Between Biomarkers and Outcome Is Well Known

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 described by a linear function.

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.
**Slide 10**

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 disease modifying effect it is small and hard to detect without withdrawal of treatment.

**Slide 11**

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.

**Slide 12**

A trial was undertaken in China 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.
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.

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.

The first patient in the DATATOP cohort shows the patterns that were eventually used to build a disease progress 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 progress model is most suitable but it could be linear. Testing different model led to the conclusion that the disease progress approached an asymptote using a Gompertz model.
Disease progress + Drug action + Dropouts Predicts DATATOP Cohort

Model includes symptomatic and disease-modifying treatment effects

The effects of levodopa and deprenyl are shown. Both have offset effects and protective 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.


ELLDOPA Study
ELLDOPA – Earlier vs Later L-DOPA

Control
● Placebo

Levodopa
● Low dose - 0.15 g/day
● Medium dose - 0.3 g/day
● High dose - 0.6 g/day

Group size - 90 patients per group

Fahn S. Parkinson disease, the effect of levodopa, and the ELLDOPA trial: Earlier vs Later L-DOPA. Archives of Neurology 1999;56(5):529-35
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.

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.


The ELLDOPA study was simulated using the model for disease progress and levodopa effects obtained from the ELLDOPA data (Predicted ELLDOPA) and the DATATOP cohort (Predicted DATATOP). 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.


The ELLDOPA trial included 4 treatment groups and the data from the placebo the low, medium and high levodopa treatment groups are shown as gray symbols in this plot. The observed median trend in these data is shown as these blue symbols whereas the observed variability for 90% of the population are shown as these dashed lines. The median trend is the result of the progression of the disease, which is assumed to be linear with a slope of nearly 12 units per year. There is a placebo effect, which is most visible in the placebo group, but also takes place in the other treatment groups. This placebo effect slowly washes in. It is transient and disappears over time. Part of the treatment effect is symptomatic, which has a rapid onset and washes out when the treatment stops after 9 months. The symptomatic effect has an Emax of 70% of baseline and an ED50 of 540 mg/d. This symptomatic effect does not describe the complete response. An additional disease modifying effect is required, which reduces the rate of progress by 32%. The median response predicted by the disease model closely resembles the observations, as the median observations fall within the 95% confidence interval (yellow area) of the predicted total effect. The same holds true for the observed variability for the total effect, which is represented by the gray area, which closely matched by the predicted variability.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Definition</th>
<th>Number of outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Death</td>
<td>Mortality at 8-years post study entry</td>
<td>98</td>
</tr>
<tr>
<td>Disability ADL15</td>
<td>Total ADL score ≥15</td>
<td>364</td>
</tr>
<tr>
<td>Cognitive Impairment MMSE24</td>
<td>Mini-mental state exam ≤24</td>
<td>89</td>
</tr>
<tr>
<td>Depression HAMD10</td>
<td>Hamilton-D score ≥10</td>
<td>183</td>
</tr>
</tbody>
</table>
Why do women live longer than men?

The hazard describes the death rate at each instant of time. The shape of the hazard function over the human life span has the shape of a bathtub. US mortality data shows the hazard at birth falls quickly and eventually returns to around the same level by the age of 60. The hazard is approximately constant through childhood and early adolescence. The onset of puberty and subsequent life style changes (cars, drugs,…) adopted by men increases the hazard to a new plateau which lasts for 10 to 20 years. It would require a time varying model to describe how development (children) and ageing (adults) are associated with changes in death rate.

Figure 2.6. Hazard functions for all cause mortality for the US population in 1980. White males (---); white females (-----); black males (-----); black females (-----).

Hazard models link disease progress and clinical outcome probability

\[
S(t) = \Pr(T \geq t) = e^{-\int_0^t h(u) \, du}
\]

\[
h(t) = \beta_0 \cdot \exp(\beta_1 \cdot \text{status}(t))
\]

Hazard Function
Survivor Function

Hazard Changes for Parkinson's Outcomes

<table>
<thead>
<tr>
<th>Explanatory factors</th>
<th>Death N=98</th>
<th>Disability N=364</th>
<th>Cognitive Impairment N=89</th>
<th>Depression N=183</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age at study entry (per y)</td>
<td>↑7%</td>
<td>↑3%</td>
<td>↑8%</td>
<td>NS</td>
</tr>
<tr>
<td>Time since entry (per y)</td>
<td>↑14%</td>
<td>↓22%</td>
<td>NS</td>
<td>↓32%</td>
</tr>
<tr>
<td>Deprenyl # (10 mg/d)</td>
<td>↑152%</td>
<td>↓36%</td>
<td>NS</td>
<td>↓37%</td>
</tr>
<tr>
<td>Disease Status (per 10 units)</td>
<td>UPDRS</td>
<td>UPDRS</td>
<td>PIGD</td>
<td>UPDRS</td>
</tr>
<tr>
<td></td>
<td>↑40%</td>
<td>↑175%</td>
<td>↑335%</td>
<td>↑43%</td>
</tr>
</tbody>
</table>

\# = Independent of disease status effect NS = not significant

Osteoporosis
Disease Progression, Drug Action -- and Fractures
The Link Between Bone Mineral Density and Outcome Is Well Known?

BMD Changes and Fracture Risk
- Positive Correlation
  - Bisphosphonates
  - SERMs
- Negative Correlation
  - Fluoride
- Poor Correlation?
  - Calcitonin
  - Vitamin D and Ca++

The link is controversial – especially for new mechanisms
Correlation is the weakest form of understanding
What can PKPD and disease progression modelling offer?

Women’s Health Initiative
Hormone Replacement Therapy (HRT) Trial

16,608 Healthy Postmenopausal Women Aged 50-79 y
- 100% Fracture Outcomes
- 6% BMD at 0, 1, 3, and 6 Years

8,506 Received Estrogen+Progestin
8,102 Received Placebo
42% Stopped Taking Treatment
38% Stopped Taking Treatment

Adapted from Rossouw JE et al. JAMA 2002; 288(3):321-333

The WHI is a series of clinical trials designed to assess the risks and benefits of different strategies to reduce the incidence of heart disease, cancer, and fractures in postmenopausal women.

One of the clinical trials in the WHI was the estrogen-progestin trial which randomized 16,600 women to either estrogen + progestin group or placebo. The trial was designed to follow these women for 9 years but after a mean follow-up of 5.2 y the study was stopped early due to increase incidence of breast cancer, heart disease and other AEs. All cause mortality was not significantly different.

During the trial a substantial number of women stopped taking their assigned treatment, 42% in the estrogen-progestin arm and 38% in the placebo arm. However, these women still provided outcome data.

By the end of the trial, fracture outcome was reported for all women.
Bone mineral density was obtained from a 6% cohort of women. This means there was 1024 women with BMD measurements.

NOTE: Ca/vitamin D at doses administered show increases in BMD without added reduction in fracture (hip and total fracture)
Baseline BMD, Age and Treatment Effect are Predictors of Fracture

Effect of BMD₀ and Ageing Placebo Only

Effect of E(D) $BMD_x = 0.982$

Baseline BMD, Age and Treatment

How Good is the Model Prediction?
WHI First Fracture

What Did We Learn?

- UPDRS is a predictor of several outcome events
  - Survival predicted by time course of disease progress
  - Deprenyl may have positive and negative benefits

- BMD is a predictor of fracture hazard
  - Slow increase in BMD due to treatment

- Biomarker link via hazard is a general mechanism for predicting outcome events
  - The missing link for translational research?

- Time cannot be ignored!

This is a deterministic simulation of the final fracture model using total body BMD.
NOTE: Ca/vitamin D at doses administered show increases in BMD without added reduction in fracture (hip and total fracture. JAMA 2006)

The disease model contained a disease status model for BMD, a dropout model and a time-to-event model for fractures. Our modeling efforts have shown that:
1) Treatment increase BMD by 6%. But due to slow bone turnover, maximum treatment effect is not observed until 4-6 years after initiating treatment.
2) Women are more likely to stop treatment within the first year of the trial and taking E+P. Within the placebo and E+P arms, women with lower BMD are more likely to stop treatment.
3) We have shown that baseline BMD and changes in BMD due to treatment are predictors of osteoporotic fractures. Our results also showed that there was no effect of changes in BMD in the placebo group on fracture risk.
Putting Time Back into The Picture

“Science is either stamp collecting or physics”
Ernest Rutherford

Stamp Collecting → Models → Physics

Biomarker + Time → Hazard + Time → Outcome