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PRACTICAL INFORMATION

Today's session includes:

- continuation of review for logistic regression,
- VER Exercise 15 (model building, `pig_adg` data): discussion/review possible, based on student feedback.

Today's lecture:

- multiple logistic regression:
 - * more on interpretation of coefficients,
 - * statistical inference,
 - * model-building: principles and procedures (focusing mostly on differences to linear regression),
- new topics for logistic regression:
 - * “likelihood”, in particular its use for maximum likelihood estimation and likelihood-ratio tests,
 - * relation to case-control studies.
- general topics (logistic regression and beyond):
 - * model selection criteria,
 - * presentation of categorical predictor effects,
- textbook (VER/MER) reading:
16.1–10 fully covered after this lecture.

DATASET NOCARDIA (VER)

- subset of a real dataset on Nocardia mastitis in Nova Scotia dairy herds collected in 1989,
- case-control study design with 54 case and control herds,
 - * 54 (all!) case herds included in study,
 - * 54 non-case herds randomly selected from population of herds,
- purpose of study: evaluate the association between various exposure variables and case-control status of the herds.

Variable	Description	Values
id	farm id	(nominal)
casecont	herd status for Nocardia mastitis	0/1 (control/case)
dcpct	percent of dry cows treated	0 – 100 %
dneo	use of dry-cow product containing neomycin	0/1 (no/yes)
dclox	use of dry-cow product containing cloxacillin	0/1 (no/yes)
dbarn	barn type for dry cows	1 = freestall 2 = tiestall 3 = other
numcow	number of cows milked	16 – 190
...

CASE-CONTROL STUDY AND LOGISTIC REGRESSION

Nocardia data: outcome=dclox(!), explanatory=casecont:

casecont	dclox		Total	Prop. exposed
	1	0		
1	8	46	54	0.148
0	19	35	54	0.352
Total	27	81	108	

Statistical model:

two binomial distributions $\text{Bin}(54, p_1)$ and $\text{Bin}(54, p_0)$ for case and control populations, respectively.

Odds-ratio (OR) for comparison of exposure in case and control populations, or for comparison of risk of exposed and non-exposed herds

$$\text{OR} = \text{odds}(0.148) / \text{odds}(0.352) = 8 \cdot 35 / (19 \cdot 46) = 0.320,$$

\Rightarrow cloxacillin treatment protective against Nocardia mast.

Logistic regression: $\text{logit}(p_i) = \beta_0 + \beta_1 \text{dclox}_i$, gives:

$$\hat{\beta}_1 = -1.138 = \ln(0.320) = \ln(\text{OR}),$$

$$\hat{\beta}_0 = 0.273 \quad \leftarrow \text{meaningless/useless!}$$

Same OR from 2×2 -table analysis and logistic regression.¹

¹ A statistical result states that under the assumption that the sampling proportions in case and control populations are independent of the predictors, a case-control study can be analysed by the same logistic regression model as if the design had been a cohort study, except that the estimated intercept is meaningless.

TWO-WAY TABLE AND LOGISTIC REGRESSION

Nocardia data: outcome=dbarn, explanatory=casecont:

casecont	dbarn			Total
	1:freestall	2:tiestall	3:other	
1	22	29	3	54
0	13	38	3	54
Total	35	67	6	108

Simple statistical model and analysis:

comparison of case and control populations of herds with respect to distribution of barn types $\sim \chi^2$ -test.

Multiple odds-ratios by focusing only on two dbarn categories at a time, e.g. involving freestall barn type:

$$\text{tiestall vs. freestall : OR} = 13 \cdot 29 / (22 \cdot 38) = 0.451,$$

$$\text{other vs. freestall : OR} = 13 \cdot 3 / (22 \cdot 3) = 0.591.$$

Logistic regression with dbarn as a categorical predictor and freestall as the reference category:

$$\text{logit}(p_i) = \beta_0 + \beta_1(\text{dbarn}=2)_i + \beta_2(\text{dbarn}=3)_i,$$

gives the estimates:

$$\hat{\beta}_0 = 0.526 \quad \leftarrow \text{meaningless/useless!}$$

$$\hat{\beta}_1 = -0.796 = \ln(0.451) = \ln(\text{OR}) \quad \text{for tiestall vs. freestall,}$$

$$\hat{\beta}_2 = -0.526 = \ln(0.591) = \ln(\text{OR}) \quad \text{for other vs. freestall.}$$

Tests of dbarn effect give P -values around 0.17 with both approaches (i.e., χ^2 -test and logistic regression).

ODDS-RATIO IN MULTIPLE LOGISTIC REGRESSION

Basic fact:

In an additive² multiple logistic regression model,

$$\text{logit}(p_i) = \beta_0 + \beta_1 x_{1i} + \dots + \beta_k x_{ki},$$

the odds-ratio for an increase of a units by predictor x_1 (say) is given by $OR = e^{\beta_1 a}$, *no matter the values of all other predictors* (as long as they are equal in the two scenarios whose probabilities we compare).

Illustration by Nocardia data and the model,

$$\text{logit}(p_i) = \beta_0 + \beta_1 \text{dneo}_i + \beta_2 \text{dclox}_i + \beta_3 \text{dcpct}_i,$$

$$\text{logit}(\hat{p}) = -2.98 + 2.21 \text{dneo} - 1.41 \text{dclox} + 0.023 \text{dcpct},$$

- compare herds with $\text{dneo} = 1$ and $\text{dneo} = 0$ (i.e., $a = 1$) and any (but same!) values of other predictors,
- compute predicted probabilities on logit scale,

$$\text{dneo} = 1 : \text{logit}(\hat{p}_1) = -2.98 + 2.21 - 1.41 \text{dclox} + 0.023 \text{dcpct},$$

$$\text{dneo} = 0 : \text{logit}(\hat{p}_0) = -2.98 + 0 - 1.41 \text{dclox} + 0.023 \text{dcpct},$$

- convert logit probabilities to odds,

$$\begin{aligned} \text{dneo} = 1 : \text{odds}(\hat{p}_1) &= e^{-2.98+2.21-1.41 \text{dclox}+0.023 \text{dcpct}}, \\ &= e^{-2.98} e^{2.21} e^{-1.41 \text{dclox}} e^{0.023 \text{dcpct}}, \end{aligned}$$

$$\text{dneo} = 0 : \text{odds}(\hat{p}_0) = e^{-2.98-1.41 \text{dclox}+0.023 \text{dcpct}},$$

- compute odds-ratio,

$$OR = \frac{\text{odds}(\hat{p}_1)}{\text{odds}(\hat{p}_0)} = \frac{e^{-2.98} e^{2.21} e^{-1.41 \text{dclox}} e^{0.023 \text{dcpct}}}{e^{-2.98} e^{-1.41 \text{dclox}} e^{0.023 \text{dcpct}}} = e^{2.21} = 9.14,$$

- recall that the `logistic` command always gives the OR for a one unit change (possibly inappropriate for continuous predictors).

² Assuming that the predictors x_1, \dots, x_k do *not* represent interaction or polynomial regression terms.

STATISTICAL INFERENCE FOR LOGISTIC REGRESSION

Estimation by maximum-likelihood method (next slides).³

Wald confidence intervals and tests:

based on estimates $\hat{\beta}_1$ (say) and standard errors $SE(\hat{\beta}_1)$:

- approximate $(1-\alpha)$ confidence interval using a standard normal reference distribution, e.g.

$$95\% \text{ CI for } \beta_1 : \hat{\beta}_1 \pm z^* SE(\hat{\beta}_1), \quad z^* = 1.96 \quad (z_{1-\alpha/2}),$$

- approximate z -tests of simple hypotheses, e.g. of $H_0 : \beta_1 = b$ vs. $H_a : \beta_1 \neq b$ by the z -statistic

$$z = (\hat{\beta}_1 - b) / SE(\hat{\beta}_1) \approx N(0, 1) \quad \text{under } H_0,$$

- multiple Wald tests possible as well (using software),
- beware that Wald procedures do not work when either estimates or their standard errors are “extreme”.⁴

Likelihood-based inference: likelihood-ratio test (next slides) and (profile) likelihood confidence interval,

- also approximate, but generally considered more precise than Wald procedures although difference often small,
- confidence intervals available in Stata using `logprof` or `pllf` add-on commands (but not core part of course).

³ Quasi-likelihood estimation is the name used for the procedure when the model contains “overdispersion” or “underdispersion” (to be discussed in a later lecture).

⁴ Occurs with perfectly fitted categories, or more generally, (quasi-)separation of parameters, see e.g. Heinze & Schemper (2002), *Statist. Med.* **21**, 2409-2419.

LIKELIHOOD FUNCTION

Simple example: binomial distribution,

- consider one group of 10 mice subjected to a particular dose, and denote by
 - * Y the no. of dead mice, assume we observed $Y = 3$,
 - * p the probability of mice dying at this dose,

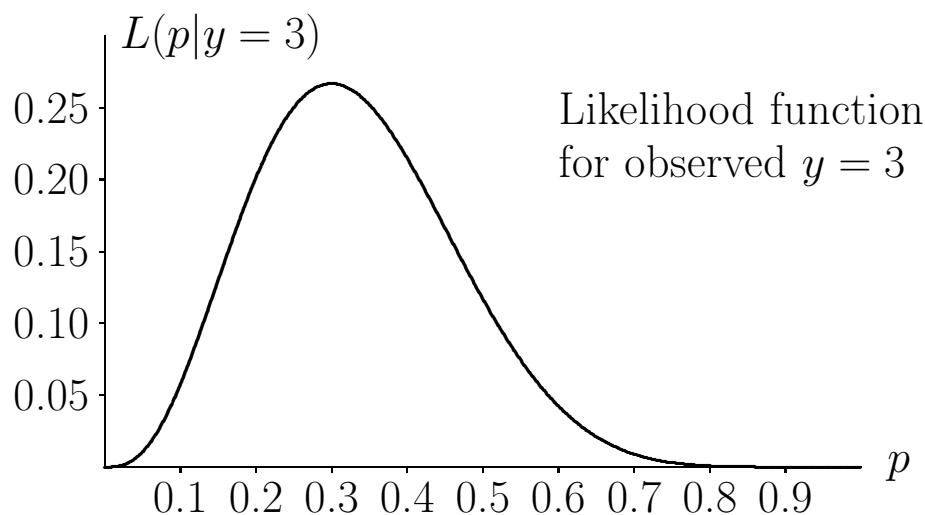
- the prob. distribution of Y is $\text{Bin}(10, p)$ with values

$$p(y) = \binom{10}{y} p^y (1-p)^{10-y}, \quad y = 0, \dots, 10,$$

and $p(y)$ is the probability of observing y dead mice,

- the likelihood function is this function viewed as a function of the unknown parameter p and taking the observed data (y) as fixed,

$$L(p) = L(p|y) = \binom{10}{y} p^y (1-p)^{10-y}, \quad 0 \leq p \leq 1,$$



In general, the likelihood function is the probability (in continuous models: density value) of the observed data viewed as a function of the unknown parameters.

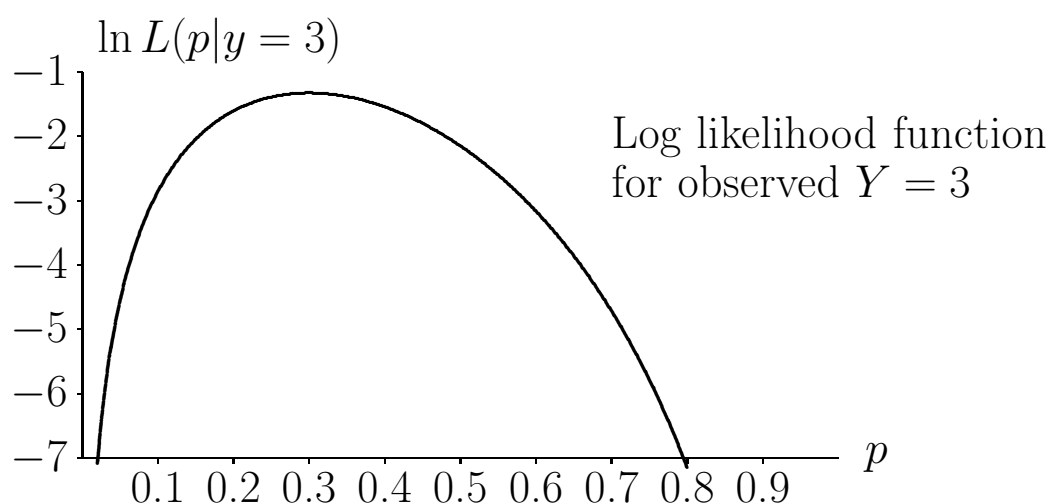
MAXIMUM LIKELIHOOD ESTIMATION

Idea: choose as our estimate the value of the parameter which *maximizes* the likelihood function = the maximum likelihood estimate (MLE),

- intuitively plausible (“make the data as probable as possible”),
- general procedure applicable to all parametric models,⁵
- easy to compute analytically in many models,
- leads to estimates with good theoretical properties, in particular in large samples.

Computing the MLE in complex models (also logistic reg.):

- iterative procedure: starting value \rightarrow improved value \rightarrow improved value $\rightarrow \dots \rightarrow$ no further improvement possible (convergence \sim maximum found, or failure),
- convenient and common to work with $\ln L$ instead of L .



⁵ In linear (regression) models, least-squares estimates are also MLEs.

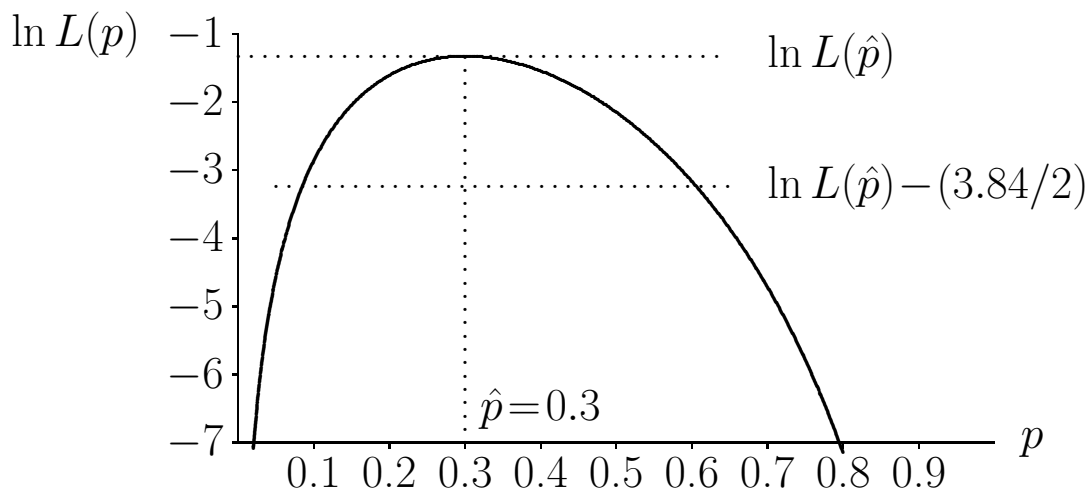
LIKELIHOOD-BASED INFERENCE

Idea: use likelihood function as our “evidence” against specific parameter values (or hypotheses),

- p 's with low likelihood seem little plausible (observed data unlikely),
- p 's with likelihood close to optimal seem plausible,
- statistical theory (based on large samples):
 - * differences in $2 \ln L \approx \chi^2$ -distribution,
 - * likelihood-ratio (LR) test, denoted G^2 , for comparing “full” and “reduced” model (submodel $\sim H_0$),

$$G^2 = 2(\ln \hat{L}_{\text{full}} - \ln \hat{L}_{\text{red}}) \approx \chi^2(\text{df}) \quad \text{under } H_0,$$
 where df = difference in no. of parameters between the models, and \hat{L} = optimal likelihood values.

Example: testing $H_0 : p = p_0$ (p_0 known)



Interpretation: no evidence against p_0 -values in the range $(0.08, 0.61)$ at the 5% significance level (so it's a 95% CI).

LR-TESTS IN LOGISTIC REGRESSION

Example I: comparing models for `nocardia` data,

Model	$2 \ln L$	params	change prev. model		
			G^2	df	P
<code>dneo,dclox,dcpct</code>	-107.99	4	—	—	—
<code>dcpct</code>	-138.15	2	30.16	2	<0.001
(intercept only)	-149.72	1	11.57	1	0.001

- both model reductions strongly significant,
- test against null model directly in Stata listing.

Example II: goodness-of-fit test for `mice` data,

Model	$2 \ln L$	params	change prev. model		
			G^2	df	P
<code>dose categorical</code>	-117.64	12	—	—	—
<code>dose continuous</code>	-127.89	2	10.25	10	0.42

- no evidence against linear relation of dose (logit scale),
- categorical model has one “perfectly fitted category” (dose = 0.1413) \Rightarrow care is needed in Stata.

(Technical) Deviance:

= difference in $2 \ln L$ between actual and “saturated” model,⁶

- can be used to compute G^2 for LR-test instead of $2 \ln L$,⁷
- can be used for goodness-of-fit test for grouped data if “saturated model” defined properly (not recommended⁸).

⁶ “Saturated” model: one parameter for every observation or every distinct group of predictor values; different uses exist within and between softwares. . . .

⁷ In my view, there is no real advantage in using the deviance instead of $2 \ln L$.

⁸ It is safer to compute the LR-test from the two model fits.

STATA DO-FILE

```
use nocardia.dta, clear
tabulate casecont dclox, chi2 row exact lrchi2
cc casecont dclox
* logistic regression for case-control design
logit casecont dclox
logit casecont dclox, or /* displays ORs */
logistic casecont dclox /* same using logistic command */
logit dclox casecont /* to demonstrate same log(OR) */
* logistic regression for categorical predictor
tabulate casecont dbarn, chi2 row exact lrchi2
logit casecont i.dbarn
logistic casecont i.dbarn
testparm i.dbarn /* multiple Wald test for dbarn */
* multiple logistic regression
logit casecont dneo dclox dcpct
logistic casecont dneo dclox dcpct /* shows ORs */
testparm dneo /* Wald test as chi^2-test, same P as z-test */
* profile likelihood CI for dneo, using logprof add-on command
logprof dneo
* display of iterations of ML estimation
logit casecont dneo dclox dcpct, trace
* likelihood-ratio tests
logit casecont dneo dclox dcpct /* need to rerun using logit */
test dneo dclox /* Wald test for dneo+dclox */
estimates store full
logit casecont dcpct
lrtest full /* likelihood-ratio test for dneo+dclox */
lrtest full, stats /* same with all fit statistics */
estimates store red
logit casecont
estimates store null
estimates stats *
estimates table *

use mice.dta, clear
logit dead dose
estimates store red
* does not work with non-integer dose values: logit dead i.dose
egen Dose=group(dose), label /* create dose groups (in new variable Dose) */
logit dead i.Dose /* dose as categorical predictor */
logit dead i.Dose, asis /* avoids exclusion of dose=0.1413 */
logit dead i.Dose, asis trace /* showing convergence process */
testparm i.Dose /* note: Wald test for dose fails here */
lrtest red, stats /* likelihood-ratio test ok */
```