Revealing gene action for production characteristics by inbreeding, based on a long-term selection experiment

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The gene action involved in the expression of production characters was investigated, using the effect of the theoretical inbreeding coefficient on the mean of the characters in a two-way selection experiment for the slope (b) and intercept (ln (a)) of the allometric function: $w = ln (a) + bv$ [where $w = ln$ (body mass) and $v = ln$ (cumulative feed intake)]. From Crow & Kimura's (1970) finding that three possibilities exist when the change in the mean of a character is plotted against the inbreeding coefficient (F), it was decided to plot the means of the characters under investigation against F, and to fit regressions to determine whether no dominance, dominance without epistasis, or dominance with epistasis were involved in the expression of these characters. It was found that dominance may be involved in all the examined characteristics except the intercept (Phase 2) and slope (Phase 2) of the allometric model and average daily feed intake (Phase 1) of the ln (a) selection group, as well as average daily feed intake (Phase 1 and 2) of the b selection group.

Die genewerking wat by die uitdrukking van produksie-eienskappe betrokke is, is ondersoek deur die effek wat die teoretiese intelingskoëffisiënt op die gemiddeld van die eienskappe het, in die twee-rigting seleksie-eksperiment vir die afsnit (ln (a)) en die helling (b) van die allometriese funksie : $w = ln (a) + bv$ [waar $w = ln$ (liggaamsmassa) en $v = ln$ (kumulatiewe voerinname)], te ondersoek. Crow & Kimura (1970) het gevind dat wanneer die gemiddeld van 'n eienskap teenoor die teoretiese intelingskoëffisiënt (F) geplot word, drie moontlike afleidings daaruit gemaak kan word. Op grond hiervan is die gemiddeldes van die eienskappe wat ondersoek is, teenoor F geplot en regressies is gepas om die veranderinge te beskryf. Uit die resultate is afgelei of geen dominansie, dominansie sonder epistase of dominansie met epistase by die uitdrukking van die spesifieke eienskappe betrokke was. Dit is gevind dat dominansie betrokke mag wees in al die eienskappe wat ondersoek is, behalwe die afsnit (Fase 2) en helling (Fase 2) van die allometriese model en gemiddelde daaglikse voerinname (Fase 1) van die ln (a) seleksiegroep, asook die gemiddelde daaglikse inname (Fase 1 en 2) van die b seleksiegroep.

Keywords: Allometric function, dominance, epistasis, inbreeding coefficient.

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Introduction

The harmful effect of inbreeding on reproductive rate and general vigour are well known to breeders and biologists (Falconer, 1981). Inbreeding increases homozygosity. Thus, one observable effect of inbreeding is that recessive genes, previously hidden by heterozygosity with dominant alleles, will be expressed. Since most such genes are harmful in one way or another, inbreeding usually leads to a decrease in size, fertility, vigour, yield and fitness (Crow & Kimura, 1970). Lush (1945) pointed out that to the extent that desirable epistatic gene combinations have been accumulated in a population under selection, such combinations may be dispersed by inbreeding, thus further reducing merit. Also, on the rare occasions when a heterozygous gene combination is preferred over either homozygous combination (as in over-dominance), inbreeding will again reduce merit.

In this study, the effect of inbreeding on production characteristics was investigated in a two-way selection experiment, where 23 generations of selection for the intercept (ln (a)) and 32 generations of selection for the slope (b) of the allometric growth function: $w = ln (a) + bv$ [where $w = ln$ (body mass) and $v = ln$ (cumulative feed intake)], were completed. The rat (*Rattus domesticus*) was used as the model for the experiment.

Materials and Methods

Facilities were available for the accomodation of four selection groups of 40 rats each. Each selection group consisted of four families with 10 individuals each (five males and five females). Within-family selection was practised so that every family would be represented in each generation and inbreeding would be kept to a minimum. Matings of least relationships were made according to the system suggested by A. Robertson (Falconer, 1973) (Table 1).

Each mated pair and its progeny were given a number, from 1 – 4. Table 1 shows the families of the mated rats and the new

Table 1 Mating schedule in the selection lines

Family of origin		New mating number
♀	♂	
1	× 2	1
3	× 4	2
2	× 1	3
4	× 3	4

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mating number assigned to the progeny. This system does not reduce the average rate of inbreeding, but it has two advantages over the cyclical system. The practical advantage is that the mating schedule is the same in every generation, the more theoretical advantage is that inbreeding coefficients are the same for all families in a generation and the rate of inbreeding is the same in all generations (Scholtz, 1987).

Please see Scholtz et al. (1990) & Mostert et al. (1994) for details regarding the selection experiment.

To make provision for infertility, the two best males and females from each family were selected from each generation. Rotational mating was practised and the best male was first mated to both the selected females. After eight days, the second best male was mated to the same females (Scholtz, 1987). With selection of an equal number from all families and as sib-matings were avoided, the effective population size could be determined as:

$$N_e = N + 2$$
$$= 18 \qquad \text{[Eq. 1]}$$

The theoretical inbreeding coefficient in any generation t could then be calculated:

$$F_t = 1 - (1 - F)^t \qquad \text{[Eq. 2]}$$

where:

$$F = 1 / (2 N_e) \quad \text{(Falconer, 1981)} \qquad \text{[Eq. 3]}$$

Family sizes varied, because sterile matings occurred and litters were standardized at 12 pups by sometimes using pups from the second best and even from the foster parents. Therefore, the correction for minimal inbreeding due to constant family size, suggested by Falconer (1981), could not be practised and Eq. 1 was used to calculate the effective population size.

Fitness is defined as the number of mature animals / female mated / 100-day period, where 'mature animals' is defined as animals being at age of joining (standardized at 90 days).

Results and Discussion

According to Crow & Kimura (1970), three possibilities exist when the change in the mean of a character is plotted against the

Table 2 Estimated regression lines, probability and R^2-values of the regressions fitted to describe the changes in the mean of the production characteristics when plotted against F (theoretical inbreeding coefficient), investigated in the long-term selection experiment where selection was practised for the intercept ($\ln(a)$) and slope (b) of the allometric model

Character	Selection group	Regression line	P	R^2
Slope Phase 2	$\ln(a)$	$y = 0.55 - 0.0001x$	NS	0.00
	b	$y = 0.57 - 0.002x + 0.00004x^2$	*	0.16
Intercept Phase 2	$\ln(a)$	$y = 1.87 + 0.0084x - 0.00018x^2$	NS	0.00
	b	$y = 1.89 + 0.012x - 0.0003x^2$	**	0.32
ADI Phase 1	$\ln(a)$	$y = 10.87 - 0.056x + 0.0014x^2$	*	0.27
	b	$y = 10.65 + 0.004x$	NS	0.00
ADI Phase 2	$\ln(a)$	$y = 17.72 - 0.07x + 0.001x^2$	NS	0.00
	b	$y = 17.98 - 0.08x + 0.001x^2$	NS	0.01
ADG Phase 1	$\ln(a)$	$y = 5.52 - 0.024x + 0.00015x^2$	*	0.27
	b	$y = 5.67 - 0.021x + 0.00001x^2$	**	0.59
ADG Phase 2	$\ln(a)$	$y = 4.87 - 0.009x - 0.0002x^2$	**	0.73
	b	$y = 5.13 - 0.038x + 0.0004x^2$	**	0.72
21-day mass	$\ln(a)$	$y = 44.7 + 0.47x - 0.011x^2$	**	0.60
	b	$y = 45.3 + 0.42x - 0.01x^2$	**	0.78
30-day mass	$\ln(a)$	$y = 81.5 + 0.39x - 0.012x^2$	**	0.43
	b	$y = 83.82 + 0.36x - 0.011x^2$	**	0.67
60-day mass	$\ln(a)$	$y = 234.05 + 0.14x - 0.016x^2$	**	0.66
	b	$y = 242.7 - 0.4x - 0.006x^2$	**	0.76
Efficiency Phase 1	$\ln(a)$	$y = 0.51 - 0.0005x - 0.00003x^2$	**	0.65
	b	$y = 0.53 - 0.002x + 0.0000034x^2$	**	0.54
Efficiency Phase 2	$\ln(a)$	$y = 0.27 + 0.0097x - 0.00004x^2$	**	0.43
	b	$y = 0.29 - 0.0015x + 0.00001x^2$	**	0.29
Total efficiency at 60 days	$\ln(a)$	$y = 0.38 + 0.002x - 0.00006x^2$	**	0.36
	b	$y = 0.39 + 0.00071x - 0.000025x^2$	**	0.36
Fitness	$\ln(a)$	$y = 8.85 - 0.25x + 0.004x^2$	**	0.49
	b	$y = 9.76 - 0.115x + 0.001x^2$	**	0.24

* $P \leq 0.05$
** $P \leq 0.01$

inbreeding coefficient (F). Firstly, in the absence of dominance, no change in the mean with inbreeding will be obtained. Secondly, when dominance without epistasis is present, the change of the mean with inbreeding is proportional to F, in other words, the change of the mean should be a straight line when plotted against F. Thirdly, if there is epistatic interaction between loci, the relationship between the mean and the inbreeding coefficient is not linear. The non-linearity is due to the interaction deviation of double, or multiple, heterozygotes. The frequency of double heterozygotes declines in proportion to F^2. Therefore, as F increases, the rate of depression of the mean increases if the interaction deviations are on average positive (reinforcing epistasis), i.e. favourable, and the rate decreases if they are negative (diminishing epistasis). No other form of interaction affects the linearity, and epistasis without dominance cannot itself cause any inbreeding depression (Falconer, 1981).

From this point of view, it was decided to plot the mean of the characters under investigation against the theoretical inbreeding coefficient (F), to determine whether no dominance, dominance without epistasis, or dominance with epistasis are involved in the expression of the characters. Regressions were fitted using Systat (1989).

By using the mean of the upward (H) and downward (L) selection lines, the effect of selection should be minimized, so that only the effect of inbreeding is observed when the mean is plotted against F.

In Table 2 the estimated regression lines, with probability and R^2-values, of the production characteristics investigated with selection for ln (a)and b, are tabulated.

From Table 2, it can be seen that there was no significant change ($P \geq 0.05$) in the mean of the slope and intercept of the allometric model, as well as in average daily feed intake (ADI) in the second post-weaning growth phase (37 – 60 days) of the ln (a) selection group.

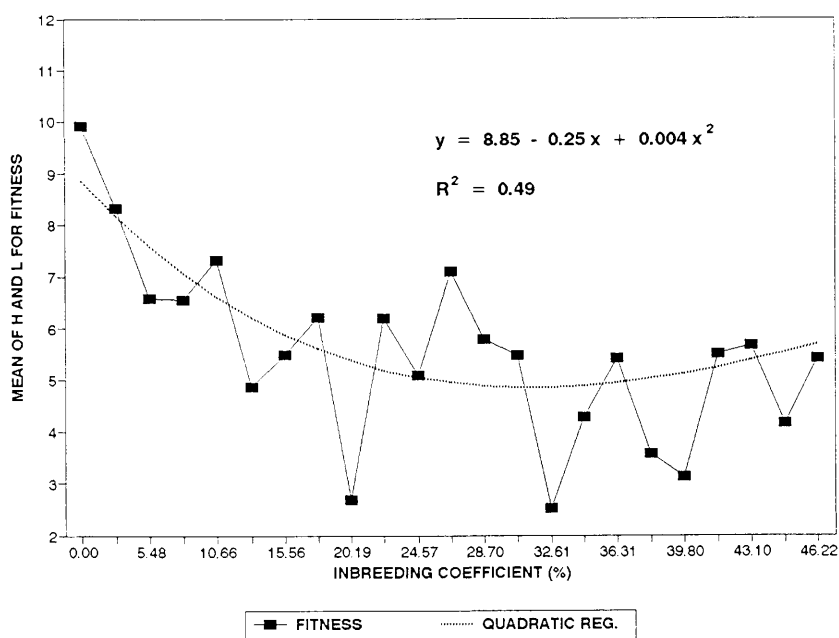The changes in the mean of ADI in the first post-weaning growth phase (24 – 36 days of age), as well as in the second post-weaning growth phase of the b selection group, also were not significant ($P \geq 0.05$) when plotted against F.

Thus, it seems that no dominance was involved in the expression of the intercept and slope of the allometric model and in ADI in Phase 2 of the ln (a) selection group, as well as for ADI in Phase 1 and 2 of the b selection group. Within loci, alleles may combine additively, but between loci additive or non-additive (epistatic) gene action may be present. Scholtz (1987) estimated the heritability of the slope of the allometric model to be 0.38 and the intercept to be 0.43. Additive gene action is thus prevalent in the expression of these characters of the ln (a) selection group. Sutherland et al. (1970) estimated a realized heritability for 4 – 11-week food intake to be 0.2 ± 0.057, while Sharp et al. (1984) estimated a realized (within-litter) heritability for 4 – 6-week food intake, adjusted for 4-week body weight, to be 0.15 ± 0.027. Non-additive gene action may thus be involved in the expression of ADI of Phase 1 of the ln (a) selection group, as well as Phase 1 and 2 of the b selection group.

A quadratic regression best described the tendencies of the means, when plotted against F, of fitness, ADI in Phase 1, ADG in Phase 1 and 2, 21-day mass, 30-day mass, 60-day mass, feed efficiency in Phase 1 and 2 and total efficiency at 60 days of age of the ln (a) selection group, as well as slope and intercept of the allometric model, ADG in Phase 1 and 2, 21-day mass, 30-day mass, 60-day mass, feed efficiency in Phase 1 and 2 and total efficiency at 60 days of age of the b selection group.

Dominance with diminishing epistasis may be involved in the expression of fitness and ADI in Phase 1 and 2 and ADG in Phase 1 of the ln (a) selection group and fitness, slope of the allometric model, ADG in Phase 1 and 2 and feed efficiency in Phase 1 and 2 of the b selection group (Figure 1).

Dominance with reinforcing epistasis may be involved in the expression of ADG in Phase 2, 21-day mass, 30-day mass, 60-day mass, efficiency in Phase 1 and 2 and total efficiency at 60 days of the ln (a) selection group, as well as the intercept of the allometric model, 21-day mass, 30-day mass, 60-day mass

$$y = 8.85 - 0.25\,x + 0.004\,x^2$$

$$R^2 = 0.49$$

MEAN OF H AND L FOR FITNESS

INBREEDING COEFFICIENT (%)

FITNESS   QUADRATIC REG.

Figure 1   The effect of the theoretical inbreeding coefficient on the mean (mean of the upward (H) and downward (L) selection lines) of fitness, as correlated response to selection for the intercept (ln (a)) of the allometric growth model.
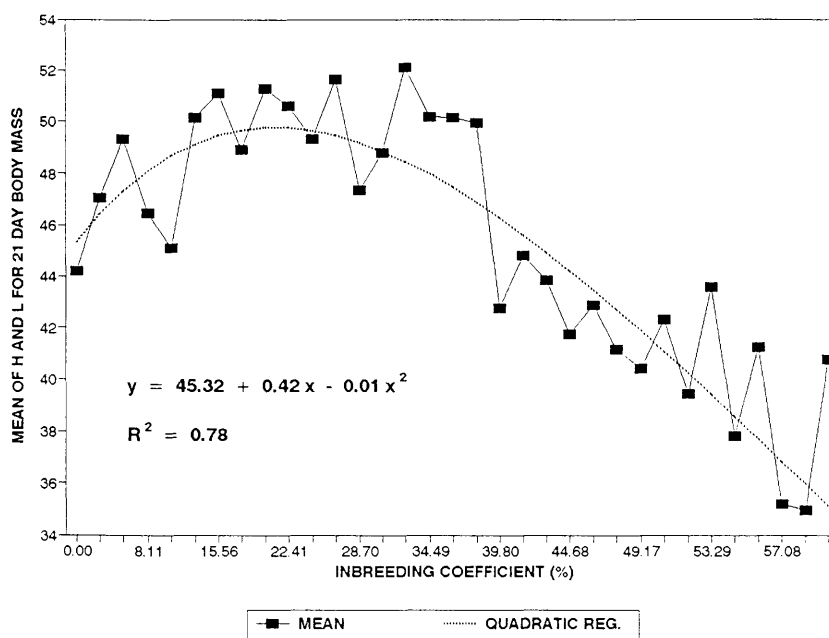
Figure 2   The effect of the theoretical inbreeding coefficient on the mean (mean of the upward (H) and downward (L) selection lines) of 21-day body mass, as correlated response to selection for the slope (b) of the allometric growth model.

and total efficiency at 60 days of age of the b selection group (Figure 2).

In the expression of these characters, dominance may be involved within loci, while between loci non-additive gene action may be present. Falconer (1981) estimated the heritability of body mass of mice at 6 weeks of age to be 0.35, while Eisen & Prasetyo (1988) estimated heritability of body mass at 12 weeks of age to be 0.43 ± 0.08. Roberts (1965) surveyed the literature on body weight of the mouse and revealed a genetic situation that is primarily additive in nature and largely uncomplicated by interactions either at the genetic level or with the environment. As mentioned before, the heritabilities of slope and intercept in Phase 2 of the allometric model were estimated by Scholtz (1987) to be 0.38 and 0.43, respectively. Eisen & Prasetyo (1988) estimated the heritability of 3 – 6-week feed efficiency to be 0.28 ± 0.09 and 3 – 6-week gain of mice to be 0.42 ± 0.06. These heritability estimates indicate that additive gene action is present in the expression of the involved characters.

The only character for which a low heritability was estimated, was feed intake (Sutherland et al., 1970; Sharp et al., 1984). Furthermore, according to Falconer (1981), in a population exposed to natural selection for an extended period under constant conditions, all the genetic variance of fitness must be non-additive, i.e. variance due to dominance and epistatic interactions, since no response for fitness can be realized through selection.

Differences exist in respect of the sign of the quadratic term between the ln (a) and b selection groups for the following characters: ADG in Phase 2, 60-day body mass and efficiency in Phase 1 and 2. This is not surprising since different sets of genes were favoured by the selection criteria in the two selection groups. A shift in gene frequencies therefore occurred between the different selection groups. The relationship between the mean of a character and the inbreeding coefficient is based on the hypothesis that no changes in gene frequency occurred. This hypothesis may therefore not hold for this study. In Table 3, a

summary is given of the gene action involved in the expression of production characteristics.

Conclusion

These results suggest that dominance may be involved in the expression of all the characteristics except intercept (Phase 2), slope (Phase 2) and ADI (Phase 1) of the ln (a) selection group and ADI (Phase 1 and 2) of the b selection group. Cross-breeding may thus be an efficient way of improving the charac-

Table 3 Summary of the gene action involved in the expression of production characteristics arising from the effect of the inbreeding coefficient on the mean of the characteristics

	Gene action	
Character	ln (a)	b
Intercept Phase 2	No dominance	Dominance (+)*
Slope Phase 2	No dominance	Dominance (–)**
ADI Phase 1	Dominance (–)	No dominance
ADI Phase 2	No dominance	No dominance
ADG Phase 1	Dominance (–)	Dominance(–)
ADG Phase 2	Dominance (+)	Dominance (–)
Weaning mass	Dominance (+)	Dominance (+)
30-day mass	Dominance (+)	Dominance (+)
60-day mass	Dominance (+)	Dominance (+)
Efficiency Phase 1	Dominance (+)	Dominance (–)
Efficiency Phase 2	Dominance (+)	Dominance (–)
Total efficiency at 60 days	Dominance (+)	Dominance (+)
Fitness	Dominance (–)	Dominance (–)

*   Dominance (+): Dominance with reinforcing epistasis
** Dominance (–): Dominance with diminishing epistasis

teristics where dominance may be involved, while other ways of improvement, such as selection, progeny testing and comparisons with collateral relatives, should be used when improving the characteristics where dominance is absent.

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