

The Application of Genetic Principles and Genetic Engineering to Improve Efficiency of Lean Meat Production

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Introduction

Efficiency of meat production can readily be improved by application of crossbreeding systems to exploit heterosis and to match characteristics of breeds to market requirements and to diverse production resources. Efficiency can also be increased by intrapopulation selection among animals by procedures available now. The potential is great for further improvements from application of rapidly evolving biotechnology. As our understanding of molecular genetics, cytogenetics and physiology evolve, this knowledge can be readily incorporated into the engineering of more efficient meat production systems. The purpose of this presentation is to briefly review the potential for application of current and evolving technology to improving production efficiency of skeletal muscle. Although the principles are similar for all species, I will draw on results from beef cattle for most of my examples because of limitations on time and my familiarity with beef cattle breeding research.

Genetic Variation Between and Within Breeds

Significant genetic variation exists between and within breeds for rate of lean tissue growth in cattle, sheep and swine. Mean breed differences and phenotypic variation within breeds for weight of retail product at 457 days of age are reflected in the frequency curves shown for seven breeds of cattle in Figure 1. These results are based on a recent

analysis of data obtained in cooperation with Kansas State University on steers produced over two generations in the first cycle of the Cattle Germ Plasm Evaluation Program at the Roman L. Hruska U.S. Meat Animal Research Center (Koch et al., 1983). Retail product is closely trimmed-boneless (trimmed to .8 mm external fat and boneless except for dorsal and transverse spinous processes remaining in short loin roasts and dorsal spinous processes and rib bones in rib roasts) steaks, roasts and lean trim. On the average, Jersey steers are more than 6 standard deviations lighter than Charolais steers. The heaviest Jersey steers are not as heavy as the lightest Charolais steers. The frequency distribution curves for all other breeds overlap. Angus and Herefords have similar means and their frequency curves overlap to a considerable degree; however, Angus and Herefords are significantly lighter than the South Devon, Limousin, Simmental and Charolais in retail product weight.

Genetic variation in retail product weight at a constant age is primarily due to additive gene effects. Effects of heterosis are low (1.4 to 3.4%, Gregory et al., 1966; Koch et al., 1983).

For some traits, it is difficult to make improvement from intrapopulation selection because genetic variation is small. This is not the case for retail product growth. Not only is there considerable genetic variation between breeds (Figure 1), but also within breeds. Estimates of the phenotypic standard deviation are 9% to 10% of the mean (Cundiff et al., 1969; Koch et al., 1983) and a high percentage of the within-breed variation is heritable (65%, Swiger et al., 1965; 64%, Cundiff et al., 1969). Thus, there is no indication that selection response has plateaued for lean tissue growth rate. When response to selection plateaus, the population is said to have reached the selection limit. Judging from experiments with laboratory species, response to selection should continue for 20 to 30 generations, and the total range in response is between 10 and 20 times the phenotypic standard deviation in the initial population (Falconer, 1960). Considering the large number of animals, and the low selection intensity in cattle relative to laboratory species, it appears conservative to estimate that selection limits would be at least 15 times the phenotypic standard deviation above the mean of present populations (Figure 2). It would appear possible to move the mean and frequency curve for retail product growth of Angus well beyond the present mean and frequency curve of Charolais. If Charolais were selected for the same criteria, it is expected that they would maintain their present 4.4 standard deviation difference for a long period of time. It is really only of academic interest whether the two breeds would

Figure 1

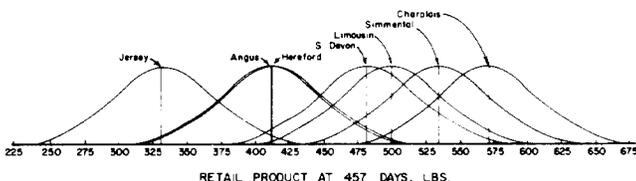


Figure 1. Distributions for breeds in retail product growth of steers to 457 days (From Koch et al., 1983).

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Figure 2

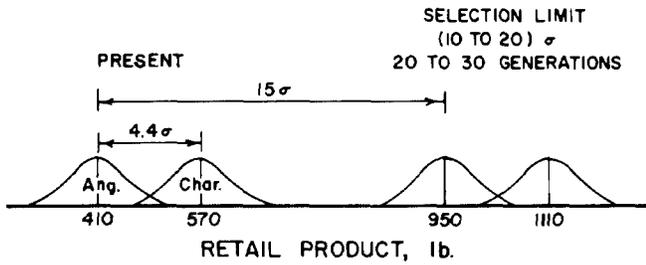


Figure 2. Frequency curves for weight of retail product in Angus and Charolais at the present time and at possible selection limits. The possible limits are based on experiments with *Drosophila* and mice (Falconer, 1960).

plateau at parallel limits (Figure 2), or the same limit, or somewhere in between. The limits would vary depending on population size (numbers), intensity of selection, and other genetic characteristics of the initial populations (Falconer, 1960). It appears conservative to estimate that at least 30 generations or about 150 years of selection would be required to move a highly heritable trait 15 phenotypic standard deviations above the present mean in breeds of cattle.

Significant genetic variation also exists between and within breeds, for efficiency of lean tissue growth from weaning to slaughter. Large differences exist between breeds for live weight gain per unit of feed (Smith et al., 1976b, Cundiff et al., 1981a, 1983) (Figure 3) and retail product growth per unit of feed (Smith, 1976), especially to weight or age end points. Heritability of retail product value less feed costs to weight or time end points is high (Swiger et al., 1965; Dickerson et al., 1974).

Figure 3

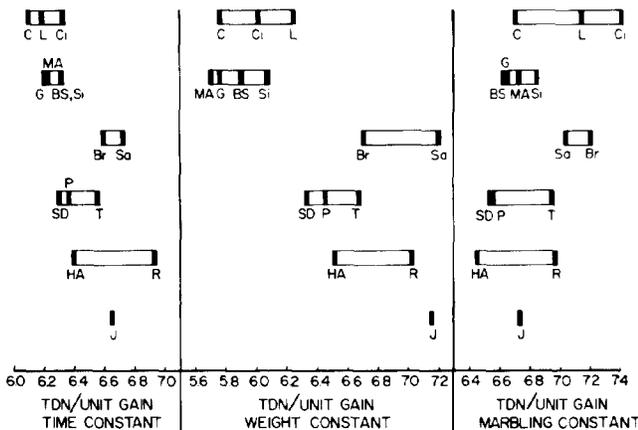


Figure 3. TDN/unit of gain in different intervals of evaluation (Breed group abbreviations are shown in table 1) (Adapted from Smith et al., 1976b, Cundiff et al., 1981b; 1983).

Trade-Offs

Because of the large amount of genetic variation between and within breeds for rate of retail product growth and for efficiency of retail product growth, it is valid to ask why more has not been done to exploit this variation. In dairy production, Holsteins, which excel in fluid milk yield, have replaced the vast majority of cows of other dairy breeds with lower genetic potential for fluid milk yield. In beef production, why haven't breeds that excel in lean tissue growth rate and size been substituted for breeds with lower lean tissue growth potential and size? The answer lies in trade-offs resulting from antagonistic genetic relationships between retail product growth rate and other traits that are important to efficiency of beef production.

For example, trade-offs of economic importance have resulted from the negative genetic relationship between efficiency of lean tissue growth rate and level of marbling required to grade USDA Choice. Choice of interval of evaluation or end point greatly influences differences and rankings among breeds for feed efficiency from weaning to slaughter (Figure 3).

Steers from faster gaining breed groups characterized by large mature size and carcasses with a higher percent retail product (Figure 4), lower fat trim, and lower marbling level

Figure 4

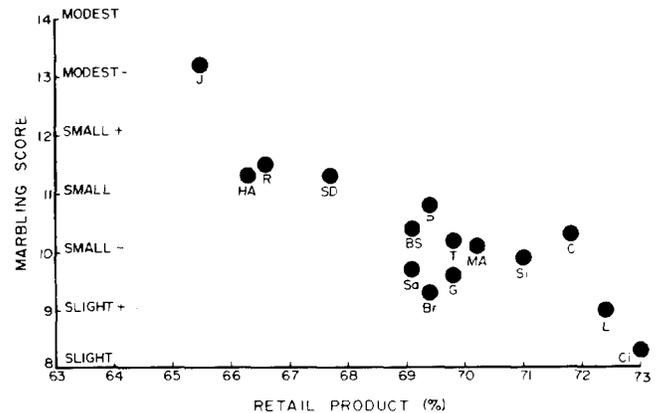


Figure 4. Relationship between marbling score and retail product percentage (Breed group abbreviations are shown in table 1) (Adapted from Koch et al., 1976; 1979; 1982a).

when compared at the same age have greater feed efficiency to a time-constant, and especially to a weight-constant end point. However, feed efficiency from weaning to a marbling end point, corresponding to the USDA Choice carcass grade, is not favorably associated with size. Breed groups with the greatest propensity to deposit marbling (those that reached the small degree of marbling in the *longissimus* muscle in the fewest days) tended to be most efficient in terms of live weight gain to the grade end point (Smith et al., 1976b; Cundiff et al., 1981b, 1983).

Evaluation to a grade-constant end point assumes that feeding to higher levels of fatness is justified in terms of improving eating quality of beef. Evaluation of flavor, juici-

ness and tenderness by trained sensory panels indicated that this assumption was not justified. When compared at the same age, although differences among breed groups were large for marbling and percent grading USDA Choice, differences in trained sensory panel evaluations for flavor, juiciness and tenderness were small (Table 1). Trained sensory panel scores did tend to increase as marbling increased when comparisons were made at the same age, but the change was slight. Furthermore, carrying cattle to a marbling end point adequate for the USDA Choice grade removes the advantage of greater feed efficiency of breeds with greater lean tissue growth potential. Breed groups with the highest marbling scores also had the lowest retail product percentages and the highest fat trim. Only limited opportunity exists from between or within-breed selection for genetic improvement of marbling, without increasing fat trim and reducing retail product (Cundiff et al., 1964; Swiger et al., 1965; Cundiff et al., 1971; Dinkel and Busch, 1973; Koch et al., 1976, 1979, 1982a).

Important trade-offs also result from negative genetic relationships among lean tissue growth rate, birth weight, calving difficulty and calf mortality. Breed relationships between calving difficulty and birth weight are portrayed in Figure 5 (Smith et al., 1976c; Gregory et al., 1978; Gregory et al., 1979). Breeds siring the heaviest calves at birth experienced more calving difficulty than breeds siring lighter calves. However, at similar birth weights, breed groups such as Chianina and Brahman crosses had less calving difficulty than Maine-Anjou and Charolais crosses, due perhaps to shape of calf or possibly other factors not now identified. Results for calving difficulty and birth weight (Figure 5) are from cows calving at 4 years of age or older. Results were pooled on this basis because cows were all 4 years old or

older in Cycle II and III of the program. The association between calving difficulty and birth weight was greater in 2- and 3-year old dams in Cycle I of the program (Smith et al., 1976c). In most breeds, calving difficulty is not a serious problem in cows calving at 4 years of age or older.

Figure 5

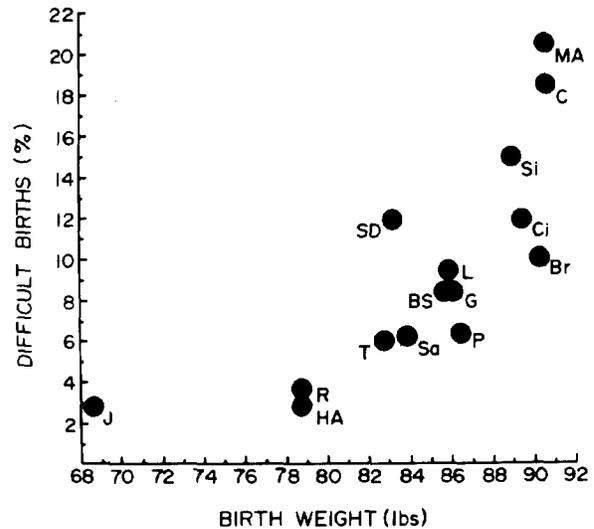


Figure 5. Relationship between calving difficulty and birth weight in calves out of cows 4-years-old or older (Breed group abbreviations are shown in table 1) (Adapted from Smith et al., 1976c; Gregory et al., 1978; 1979).

Table 1. Breed Group Means for Factors Identified with Meat Quality at 458 Days of Age

Breed crosses	Marbling ^a	Percent choice	Warner-Bratzler		Juiciness ^b	Tenderness ^b
			Shear (lb)	Flavor ^b		
Chianina-X (Ci)	8.3	24	7.9	7.3	7.2	6.9
Limousin-X (L)	9.0	37	7.7	7.4	7.3	6.9
Braham-X (Br)	9.3	40	8.4	7.2	6.9	6.5
Gelbvieh-X (G)	9.6	43	7.8	7.4	7.2	6.9
Sahiwal-X (Sa)	9.7	44	9.1	7.1	7.0	5.8
Simmental-X (S)	9.9	60	7.8	7.3	7.3	6.8
Maine-Anjou-X (MA)	10.1	54	7.5	7.3	7.2	7.1
Tarentaise-X (T)	10.2	60	8.1	7.3	7.0	6.7
Charolais-X (C)	10.3	63	7.2	7.4	7.3	7.3
Brown Swiss-X (BS)	10.4	61	7.7	7.4	7.2	7.2
Pinzgauer-X (P)	10.8	60	7.4	7.4	7.2	7.1
South Devon-X (SD)	11.3	76	6.8	7.3	7.4	7.4
Hereford-Angus-X (HA)	11.3	72	7.3	7.3	7.3	7.3
Red Poll-X (R)	11.5	68	7.4	7.4	7.1	7.3
Jersey-X (J)	13.2	85	6.8	7.5	7.5	7.4

^aMarbling: 5 = traces, 8 = slight, 11 = small, 14 = modest, 17 = moderate.

^bTrained sensory panel scores: 2 = undesirable, 5 = acceptable, 7 = moderately desirable, 9 = extremely desirable.

Neither maximum nor minimum levels of performance are optimum for many traits affecting economy of beef production. For example, French scientists (Menissier and Foulley, 1977) have suggested that calf mortality is lowest at intermediate birth weights (Figure 6). Calves that are too light at birth

yearling weight or 3) an index of yearling weight and muscling score relative to unselected controls.

Important genetic antagonisms also result from high genetic correlations among weights at weaning, yearling and mature ages (Brinks et al., 1964; Koch et al., 1973; Smith et al., 1976a). When considered alone, heavier weaning and yearling weights contribute to production efficiency. As stated earlier, cattle of larger size and heavier yearling weights require less feed per unit of gain and weight end points (Smith et al., 1976b; Cundiff et al., 1981b, 1983; Koch et al., 1982b). However, other consequences are that selection for growth also increases mature size. Breeds that excel in retail product growth are also larger in mature size (Cundiff et al., 1981a). Heavier mature weight of cows increases output per head, but also increases nutrient requirements per head for maintenance of the cow herd. Thus, output per unit of input of the production system is not affected.

Ferrell and Jenkins (1982) estimated annual metabolizable energy requirements of cows of four different biological types (Figure 7). Angus x Hereford or Hereford x Angus

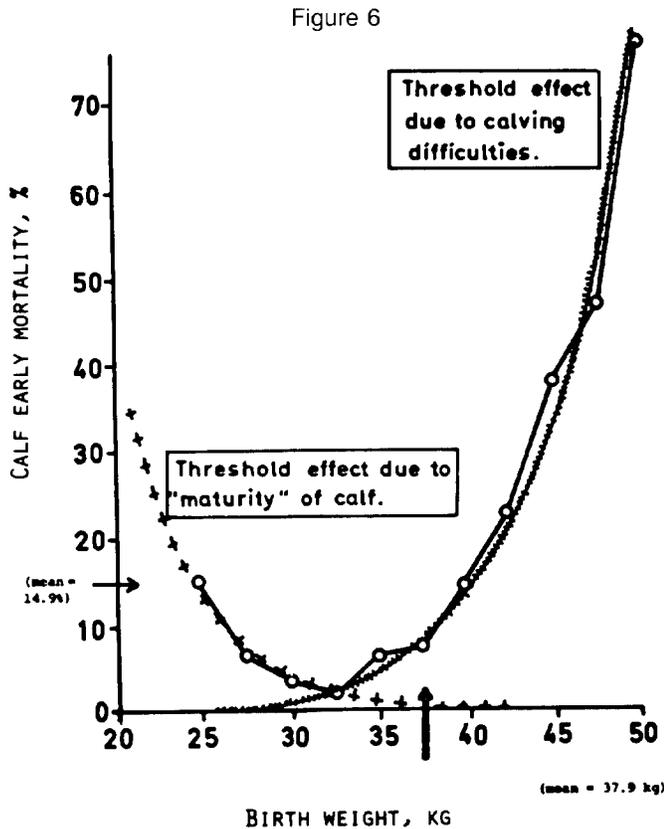


Figure 6. Relationship between early calf mortality and calf birth weight (Menissier and Foulley, 1977: citing Remmen).

tend to be premature, weak and unable to cope with stresses that naturally confront the newborn. High mortality in newborn young with light birth weight is most evident in calves born as twins or in sheep and swine born in large litters (Cundiff et al., 1982). On the other hand, calves that are too heavy experience difficult deliveries at birth. Calving difficulty is in turn associated with increased mortality. Calf mortality is about four times greater in calves experiencing difficult births than in calves experiencing no difficulty (Laster and Gregory, 1973). Calving difficulty also reduces rebreeding performance of dams (Laster et al., 1973).

We are more aware of the problem with heavy calves at birth because selection for higher growth rate has increased birth weights above their optimum range. This is not just a between-breed phenomenon, caused by mating females from breeds or crosses of small to intermediate size to sires of a different breed of larger size. Koch et al. (1982b) have shown that calving difficulty and calf mortality have increased significantly in offspring of 2-year-old first calf heifers in three lines of Hereford cattle selected for 1) weaning weight, 2)

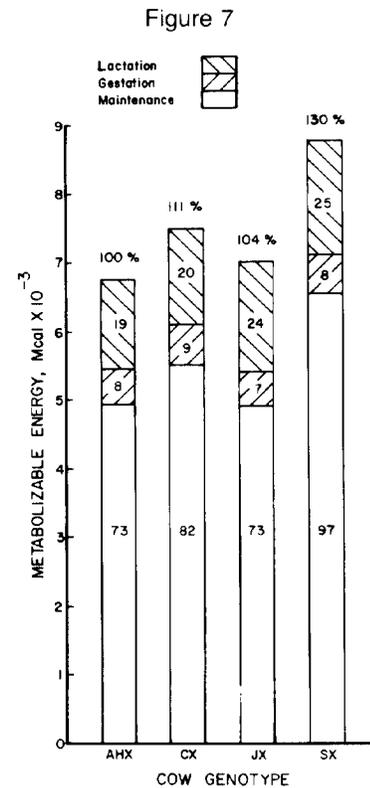


Figure 7. Estimated annual metabolizable energy requirements of cows of different biological genotypes (Ferrell and Jenkins, 1982).

(AHX) and Charolais x Angus or Charolais x Hereford (CX) cows have been characterized as having low milk production potential, while the Jersey x Angus or Jersey X Hereford (JX) and Simmental x Angus or Simmental x Hereford (SX) cows have high milk production potential. The JX and AHX cows are of small or medium mature size, while the CX and SX cows are of large mature size.

Total annual ME requirements of the SX, JX and CX cows

were 30%, 4% and 11% greater than those of the AHX cows (Figure 7). Maintenance accounted for 70% to 75% of the total annual ME requirements of each cow type. Differences in gestation and lactation requirements were evident, but requirements for these functions represented relatively small proportions of the total. Total ME consumed by weaned progeny during a 217-day postweaning feeding period were added to annual cow requirements (Figure 8) and used to estimate output/input of production of retail product (retail

Figure 8

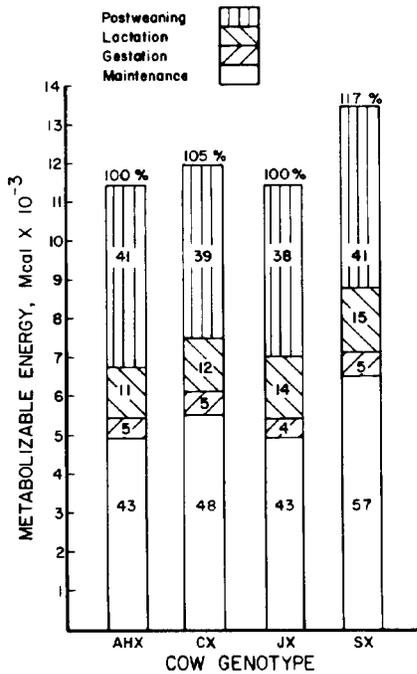


Figure 8. Estimated total metabolizable energy required for the production of calves to 455 days of age (Ferrell and Jenkins, 1982).

product weight divided by total ME consumed by the calf postweaning and the cow). Efficiencies of production were .0369, .0368, .0344 and .0336 lb/Mcal for AHX, CX, JX and SX type cows to the age end points. Thus, additional outputs of progeny by larger type cows (e.g. CX vs HAX) were offset by greater inputs. Increased feed requirements for higher levels of milk production were not offset by increased outputs of retail product.

Dickerson (1982) has shown that feed requirements for maintenance of breeding animals represents a much larger proportion of total feed costs for beef and sheep production than for pork or poultry production (Figure 9). Feed costs for maintenance of breeding animals is negatively correlated to reproductive rates among species.

Managing Trade-Offs

Because there are genetic antagonisms among fitness and growth traits, it is not possible for any one breed to excel in all characteristics of economic importance. Nor is it possible to expect simultaneous improvement in all characteristics from selection within breeds. Use of crossbreeding programs

that exploit complementarity, heterosis and opportunity to synchronize genetic resources with market requirements and feed resources provide the most effective means of managing trade-offs that result from genetic antagonisms. Complementarity (Cartwright, 1970) is exploited in specialized crossbreeding systems when crossbred cows of small to medium size and optimum milk production (maternal breeds) are mated to sires of a different breed noted for rapid growth rate and carcass leanness (terminal sire breeds). For example, heterosis and complementarity are both exploited to their fullest by combined rotational-terminal-sire systems (Gregory and Cundiff, 1980) of crossbreeding (Figure 10). Notter et al. (1979) demonstrated that this type of system can reduce break-even costs of production 4% to 5% relative to rotational crossbreeding alone.

Figure 9

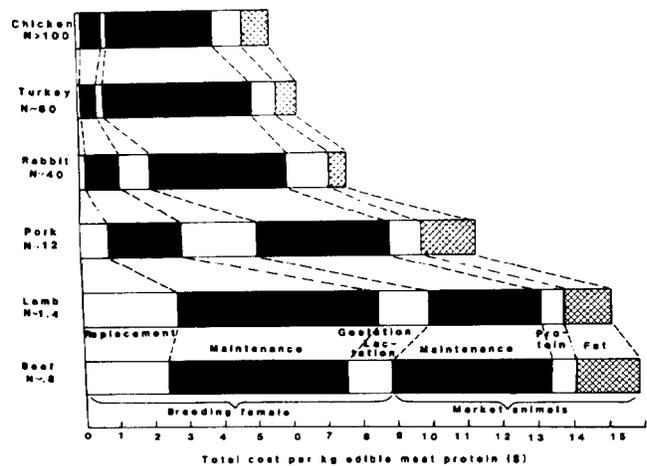


Figure 9. Total life-cycle per unit of edible meat output, partitioned by components of energy use, for meat animal species (\$) (Dickerson, 1982).

Figure 10

System	Diagram	Het.	Comp.	Wean. wt. per cow exposed
Rotational		+++	+	20%
Static-terminal-sire		+	+++	19%
Rotational-terminal-sire		+++	+++	21%

Figure 10. Use of heterosis and complementarity with alternative crossbreeding systems.

Biotechnology

As Robertson (1982) articulated in a recent symposium on "genetic engineering in animal improvement," livestock have generally been improved by simply mating the best to the best with little understanding of underlying biochemical and physiological mechanisms. Major contributions by quantitative geneticists have included clarification of what constitutes "best" and development and application of biometrical procedures which increase accuracy of identifying the "best" animals. Molecular genetics and other biotechnologies offer new possibilities for improving efficiency of production. Brief commentary regarding some of the more promising technologies follows:

Gene transfer. Genetic materials being isolated, cloned and transferred from one species to another. For example, Palmiter et al. (1982) recently transferred the structural gene for rat growth hormone fused to DNA fragments containing the mouse metallothionein — I gene into pronuclei of fertilized mouse eggs. Of 170 eggs microinjected, 21 animals developed, 7 of which carried the fusion gene. The mice carrying the gene for rat growth hormone grew 45% faster than mice not carrying the gene. Positive correlations were noted between the number of copies transferred, growth rate and level of growth hormone. One of the mice transmitted the MGH genes to half (10 to 19) of its offspring, indicating that the rat growth hormone genes were introduced into one of its chromosomes and are expected to function in subsequent generations as mouse germ plasm. Thus, this kind of technology could lead to major breakthroughs in improving resistance to disease, reproduction rates, growth and lactation in livestock species.

Active immunization. Active immunization techniques are being applied, not only to prevent disease, but to promote growth (Spencer et al., 1983) and reproduction (Wise and Schanbacher, 1983). Spencer et al. (1983) demonstrated that weight gains and growth hormone levels were significantly increased in lambs immunized against their own somatostatin, a hormone which inhibits the release of growth hormone as well as insulin and thyroid stimulating hormone. This technology could have more to offer in managing trade-offs resulting from antagonistic genetic relationships (i.e., increasing lean tissue growth efficiency without increasing feed requirements for maintenance of breeding animals with large mature size) than gene transfer.

Cytogenetics. Several chromosome abnormalities have been found which are associated with infertility in animals (e.g., Robertsonian translocation in cattle; reciprocal translocations in pigs; Popescu, 1982). Banding methods have increased accuracy of chromosome identification and classification of karyotype in domestic animals. It has been possible to map genes of translocated segments of the chromosome (Lin, 1982). Lin reported that over 400 genes have been mapped in man, while in cattle, sheep and swine only 19, 16 and 5 have been mapped, respectively. Much more work is needed on gene mapping in livestock species. Gene mapping could aid in identifying genes with major effects on components of lean growth efficiency.

Major genes. Major genes with large effects on carcass composition have been identified in cattle and swine (Hanset, 1982). The "double muscling" gene has been used to increase beef carcass leanness in certain areas in Europe

(e.g., Belgian Blue and White cattle). However, it has not been exploited in most countries because of undesired effects on dystocia and fertility. In swine, stress susceptibility expressed in pigs subjected to Halothane anesthesia is inherited as a single recessive (Ha1^s). Although the gene has favorable effects on carcass leanness, it has undesired effects on pork quality (PSE meat), and growth rate as well as mortality associated with stress susceptibility.

Piper and Bindon (1980) identified a major gene affecting fecundity in Booroola Merino sheep. They reported evidence that the mode of gene action is additive for ovulation rate, but almost completely dominant for litter size. The gene is being introduced by selective backcrossing into other populations of sheep at the present time in Australia and New Zealand. It is exciting to speculate on the possibility of one day transferring the "Booroola" gene from sheep to cattle.

As we gain greater understanding of the molecular and physiological basis of inheritance, individual genes with major effects may become more evident, much as they have in humans (Roberts and Smith, 1982). Should this occur in livestock species for traits such as lean tissue growth efficiency, the knowledge can be quickly used because the theory and application are available for their exploitation (Roberts and Smith, 1982).

Summary

Significant genetic variation exists among and within breeds of cattle for lean tissue growth rate. However, breeds that excel in lean tissue growth rate have not been substituted for breeds with less genetic potential for growth because of trade-offs resulting from antagonistic genetic relationships among economically important traits. Cattle that gain more efficiently from weaning to slaughter and excel in yearling weight and carcass cutability are obviously favored in the feedlot and market place. However, other consequences are that the selection for growth at weaning or yearling ages increases birth weight and mature weight. Increased birth weight leads to increased calving difficulty, reduced survival and reduced rebreeding in dams. Heavier mature weight increases output per cow, but also increases nutrient requirements per cow for maintenance with limited impact on efficiency of the production system. Crossbreeding systems that exploit heterosis and match characteristics of breeds to market requirements and diverse feed resources offer the most effective means of managing these trade-offs.

The potential may be great for further improvements from gene transfer, active immunization, cytogenetics, major gene exploitation and other rapidly evolving biotechnologies. As our understanding of molecular genetics, cytogenetics and physiology evolves, this knowledge can be incorporated into the engineering of more efficient meat production systems.

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