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INHERITANCE OF BOVINE DWARFISM AND THE DETECTION OF HETEROZYGOTES

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The incidence of dwarfism is increasing in registered and commercial beef herds throughout the United States. The dwarfism is conditioned by an autosomal recessive gene with complete penetrance. Breeders definitely, though unconsciously, favor the heterozygote in the selection of sires. The dwarf gene in the heterozygous state has such a marked effect upon the frontal bones that heterozygous and homozygous normals can be differentiated, with a high degree of accuracy, from the relationships of the diagnostic points on the head profile. Several different means have been developed for distinguishing the dwarf-carrier and dwarf-free genotypes in mature bulls. Tests in the field under varying conditions indicate that it is feasible to use this method of diagnosis for differentiating between dwarf-carrier and dwarf-free bulls for breeders and commercial cattlemen. The organization of such a program and the problems to be overcome are herein discussed.

This is a report of some of the research work on the California phase of a regional cooperative study in the Western States on Project W-1, "Improvement of Beef Cattle Through the Application of Breeding Methods," which is partially supported by the Research and Marketing Act of 1946 funds, and is carried on in cooperation with the staff for Beef Cattle Research of the Bureau of Animal Industry, United States Department of Agriculture stationed at Denver. The New Mexico and Arizona Experiment Station herds provided critical data.

The Western Region comprises the following states and territories:

Alaska Agricultural Experiment Station
Arizona Agricultural Experiment Station
California Agricultural Experiment Station
Colorado Agricultural Experiment Station
Hawaii Agricultural Experiment Station
Idaho Agricultural Experiment Station
Montana Agricultural Experiment Station
Nevada Agricultural Experiment Station
New Mexico Agricultural Experiment Station
Oregon Agricultural Experiment Station
Utah Agricultural Experiment Station
Washington Agricultural Experiment Station
Wyoming Agricultural Experiment Station

H I L G A R D I A

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INHERITANCE OF BOVINE DWARFISM AND THE DETECTION OF HETEROZYGOTES[1]

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HEREDITARY DWARFISM is of common occurrence in registered herds of the major beef breeds. Reports from cattlemen throughout the United States indicate that the incidence of dwarfism is also increasing in commercial herds. This study is directed toward the type of dwarfism studied by Johnson *et al.* (1950), Gregory *et al.* (1951, 1952), Carroll *et al.* (1951), and Lindley (1951). The first reference to this form of dwarfism, which is also present in Angus and Shorthorn cattle, seems to be Craft and Orr (1924). Among the other types of hereditary dwarfism in the major beef breeds is a type called "Stumpy," characterized by a curly coat, which has been reported in Shorthorns by Baker *et al.* (1950). Stumpy calves, although capable of reproduction, lack size and vigor and are generally unthrifty. Another morphological type of dwarfism apparently conditioned by a recessive gene has been reported in Angus by Baker *et al.* (1951). One of the outstanding characteristics of this type is a long head. The authors have encountered in the field what appear to be three other distinct morphological types of dwarfism in the beef breeds that have not as yet been reported. Thus it is certain there are several distinct morphological types of hereditary dwarfism in the major beef breeds.

This report will be confined almost exclusively to dwarfism of horned Herefords and the phases concerning heterozygous expression. The identification of heterozygous and homozygous normal genotypes will be limited to males. This type of dwarfism is characterized by stunted growth, pot belly, heavy breathing, a broad head, a bulging forehead, and a disproportion between the upper and lower jaw resulting in serious malocclusion.

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These characteristics are the morphological manifestations of the syndrome of cretinism. Most dwarfs can be recognized at birth by the disproportion between the upper and lower jaw, the bulging forehead, and the mature appearance. In an occasional animal, however, the characteristic does not become manifest until the animal is six weeks or more of age. Dwarfs have low vitality, in general, and the mortality is higher than in normal cattle. The animals are unthrifty and grow slowly, and they have a strong tendency to bloat; in fact, severe bloating is often the cause of death. Those that live do not fatten well and have low-grading carcasses of such quality that most are used for ground meat. Reports are that packers are discriminating against dwarfs to such an extent that they command a very low price.

INHERITANCE

Since the fecundity of the cow is relatively low, inheritance of dwarfism must be studied in small sibships. Appropriate methods must be employed to take out the bias always present in such data. All the investigators who have studied this form of dwarfism report that it is conditioned by an autosomal recessive gene (Johnson *et al.*, 1950; Gregory *et al.*, 1951; and Lush and Hazel, 1952). As yet, however, no one has provided proof of the mode of inheritance. The inheritance was studied in one large herd in which there was a relatively high frequency of the gene. A post-probant analysis of the data indicates that one autosomal recessive gene with complete penetrance is involved (table 1).

TABLE 1

POST-PROBANT ANALYSIS OF THE INHERITANCE OF DWARFISM*

	Normal	Dwarf
Observed	46	15
Expected	45.75	15.25

$X^2 = 0.00545$.

* Data from one herd.

Since the probant materially reduces the numbers, these same data were analyzed by a method that would correct for bias in small sibships but would allow the use of a few more animals than is permitted in table 1. The formula employed in table 2 is $q^1 = \frac{q}{1-p^n}$ (Apert, 1914; Stern, 1949). The expected number of dwarfs is 116.247, and the observed number is 116. When each probant is subtracted, the number of effective recessives observed for the test of inheritance is actually 20, compared with a theoretical expectation of 20.2. The total number of dwarfs is given to provide an idea of the incidence that may occur. Thus both methods of analysis are in complete agreement and indicate that an autosomal recessive gene with complete penetrance conditions the inheritance of this specific type of dwarfism.

Since it is certain that more than one type of dwarfism in Herefords is gene-conditioned, confusion could arise concerning the heredity of a specific type if different genes conditioning similar or somewhat similar phenotypic

dwarf forms were segregating simultaneously in a population. There is evidence that this situation actually exists. Reports have come from herds in which comprest bulls and cows were mated *inter se* and produced well over 25 per cent dwarfs. None of these herds has been studied in detail. Pedigree analyses clearly show that the majority of dwarfs come from the mating of normal bulls with normal cows. There are authentic pedigrees in which dwarfs, phenotypically similar to the preceding ones and assumed to be genetically identical, are produced when one parent is normal and the other comprest. According to Stonaker (1953)[7], comprest is incompletely dominant, and heterozygotes can be recognized by their shorter stature;

TABLE 2

APPLICATION OF THE *A Priori* METHOD FOR DETERMINING THE PRESENCE OF AUTOSOMAL RECESSIVE INHERITANCE OF DWARFISM IN HEREFORD CATTLE*

Size of sibship (n)	No. of such sibships (x)	Expectation (q^1 n)	Total affected, expected (q^1n x)	Total affected, observed
1	28	1.0	28.000	28
2	36	1.143	41.148	50
3	15	1.297	19.455	16
4	10	1.463	14.630	14
5	3	1.640	4.920	3
6	2	1.825	3.650	2
7	..	.....	.....	..
8	2	2.222	4.444	3
Totals	96	.....	116.247	116.0

* Data from the same herd used in the post-probant analysis.

when comprest bulls are mated to normal cows the progeny are normal and comprest in equal proportions; furthermore, when comprest are mated to comprest, 25 per cent of the progeny are afflicted with a type of dwarfism phenotypically somewhat similar to that which segregates from the mating of normal animals. This investigator further states that the dwarfism caused by two semi-dominant comprest genes (comprest dwarfs) is more severe and less viable, and is generally characterized by crooked legs. When the incidence of dwarfism exceeds 25 per cent by a significant amount in the comprest × comprest matings, there must then be more than one type of dwarfism segregating. The excess of dwarfs over 25 per cent could be accounted for by the recessive type with which this report is primarily concerned. A detailed study of the dwarfs produced from comprest × comprest matings, in herds where the incidence of dwarfism exceeds 25 per cent, should help clarify the relationships of these two types of dwarfism. Since the several different mutations that condition dwarfism in cattle are probably common to all breeds, the genetic relationships of all the dwarf genes are of substantially the same import to each breed. The remainder of this report will deal primarily with heterozygous expression of the dwarf gene and the identification of heterozygous and homozygous normal genotypes.

[7] Personal communication.

STOCKS, SOURCE, AND COLLECTION OF DATA

It was suspected that the breeder recognized and favored some distinctive characteristic or characteristics associated with heterozygous dwarf carriers, yet the effect was so intangible that it could not be defined or identified from visual inspection. The approach, therefore, was to examine in minute detail the body form of homozygous normal, heterozygous, and dwarfs and to compare specific characteristics of the different genotypes. Since it was impossible to assemble at an experiment station or laboratory all the animals to be studied, arrangements were made with individual breeders to study the animals at their respective ranches. A few dwarfs were kept under laboratory conditions for study at the California Agricultural Experiment Station. Thus all the data on normal animals were collected from breeders and a few Experiment Station herds. There were many problems to be surmounted. Because of their low fecundity and long life cycle, cattle are poor genetic material under optimum conditions, in which the investigator has complete control of matings and management and ample opportunity for observations. Breeders of registered animals are the only ones who generally keep pedigree records; therefore, this study had to be limited almost exclusively to registered herds. Since registered breeders use only a small percentage of the bulls for herd sires, the study was limited to a highly selected population, offering opportunities for a selection bias. Occasionally a herd bull was found that proved by progeny test to be free from the dwarf gene. The proving was usually by fortuitous matings. Often it was possible to determine the exact probability that a bull was homozygous. The general practice followed by most commercial breeders rarely yielded specific data on individual animals.

It became apparent early in the study that bulls were more favorable material than cows because an appreciable number could be found that were progeny-tested and their genotype for dwarfism determined. Ordinarily, a cow cannot produce enough test progeny to prove her homozygous normal. Cows have another disadvantage—their basic head shape is such that there is a greater tendency among them for the expression of the dwarf gene to be masked. Thus genotypically normal bulls may be considered in three categories, heterozygous, homozygous, and unproven; cows in two, heterozygous and unproven. Herds were studied in California, Arizona, New Mexico, Montana, Wyoming, Texas, Oregon, Utah, Oklahoma, Nevada, Washington, and South Dakota. Also, data were sent in by collaborators from the Corn Belt, eastern, and southern states. The first six states named provided most of the data.

The earlier breeders who collaborated were those who were for the most part experiencing considerable difficulty from dwarfism. Later, as the need in this study for proven homozygous normals became acute, an effort was made to locate breeders whose herds were free from, or had a low frequency of, the dwarf gene. Represented in the data are animals of the most popular breeding and blood lines throughout the United States; also represented are a few herds of less popular breeding but closely related to animals of more popular breeding. Most of the breeders who collaborated supplied

accurate information to the best of their knowledge. The possibility of inaccuracies from several sources was always present. There was little doubt about the status of a bull which the owner stated was a dwarf producer. The breeder realized the implications involving his herd and potential sales when a bull was listed as a dwarf carrier. It was the animals alleged to be free from dwarfism that caused concern. *The chief difficulty was that many breeders failed to understand the mechanics of the progeny test and the laws of probability upon which it was based.* As the study progressed, many breeders began progeny-testing sires in a systematic manner.

The measurements could be taken only when the animal was restrained. Most ranches were equipped with a squeeze or chute, the most satisfactory method of control. When there was no such equipment, it was necessary to resort to less satisfactory improvisations for restricting movement. The tattoo number or horn brand served to identify each individual. Later, the registration number and the official name were added to the information. The genotype with respect to dwarfism, sex, date of birth, and whether polled, horned, or dehorned was also indicated. The most pertinent data obtained concerning the expression of the dwarf gene were head length, head width, and the median and off-center profiles. A detailed sketch was made of the head indicating the nature of the frontal eminence, the condition of the frontal suture, the type of longitudinal and transverse dish, the nature of the orbital arches, and the type of occlusion of the incisors on the dental pad. The median head profile was obtained as described by Gregory and Brown (1952).

Data in this study were collected by several different investigators. Gregory collected the data used in establishing the diagnostic points and the key and discriminant functions, and to check these functions he also collected a new series of data from approximately 75 proven animals. Since it was desirable to have more complete checks and to determine whether it was possible for one who had never seen an animal to predict the genotype with respect to the dwarf gene, if the measurements and profiles were supplied by someone else, extensive tests were made to explore that possibility. Roubicek, working alone and at times with others, collected data on many bulls, some of proven genotype, from the states of Wyoming, Colorado, Utah, Nebraska, and Arizona. Stratton collected considerable data from breeders in Wyoming. Roubicek and Stratton working together collected data from 26 herds in Montana. Dr. Leslie E. Johnson, regional coordinator for the north-central region of the Bureau of Animal Industry, U.S.D.A., collected data from several of the Corn Belt states, including Nebraska, Kansas, South Dakota, Michigan, Indiana, and Ohio (and perhaps some others). Dr. E. J. Warwick, regional coordinator of the southern region for the Bureau of Animal Industry, U.S.D.A., collected limited data from the southern region, largely from Tennessee. Professor W. W. Galgan of Washington State College also provided a few data from the state of Washington. Limited data on proven animals have also been provided in a few instances by County Agents and Extension Specialists.

These data consisted of head profiles along with head length, head width, and age of the animals. The usual plan followed was for the collector to

withhold the complete identity and genotype of the animal until it was classified at the central laboratory by Gregory. After his commitment of genotype was in the hands of the collector, the results of the progeny tests were sent to the central laboratory. All the data collected to check the validity of the key and the discriminant functions are pooled in this report.

ANALYSIS OF DATA

Distribution of the Dwarf Gene

At the time the study was initiated it was difficult to determine the frequency of the dwarf gene within a herd, and impossible to determine the frequency in the population as a whole. A survey was made from 1950 to

TABLE 3

SUMMARY OF A SURVEY MADE DURING 1950, 1951, 1952, AND 1953 TO DETERMINE THE EXTENT OF DWARFISM IN INDIVIDUAL HERDS

Type of study	Total herds studied	Genotype of sires and cows with respect to dwarf gene				Number of herds that reported dwarfs	Registered herds	Commercial herds
		Sires			Cows			
		Heterozygous	Homozygous	Unproven	Heterozygous			
Extensive study	47	160	14	174	268	43	47	0
Mean per herd	..	3.40	0.30	3.70	6.04	..	..	..
Not detailed, but the limited data are authentic	42	35	....	....	72	41	33	9
Mean per herd	..	0.83	....	....	1.71	..	..	..

1953 of registered herds from the western states. Results are summarized in table 3. There is no claim that the 47 herds intensively studied are representative as far as gene frequency is concerned. Most of the owners realized that they had a dwarf problem, and they collaborated in the hope that a control solution could be found. A few herds were selected because they were assumed to be free from the dwarf gene. Thus the herds in the survey had both high and low frequencies of the dwarf gene.

The 42 herds with limited data are a heterogeneous group. They had both large and small numbers of breeding cows, and most were only beginning to get dwarfs. In a few of these herds dwarfism had obviously become an acute problem, but detailed studies were prevented by reluctance on the part of the owners to disclose the extent of the problem that a herd analysis would divulge. In addition to the 89 herds studied, many breeders and cooperators have provided additional data.

The studies reveal that the dwarf gene is widespread in both sires and dams and that the problem transcends the interests of breeders, commercial cattlemen, and breed associations. It is a problem that affects the economy and well-being of the industry. The working hypothesis was that dwarf carriers were favored as breeding stock in one or both sexes.

Heterozygous Expression

A gross examination of the median head profiles revealed that dwarfs of all ages unmistakably possessed bulging foreheads not present in homozygous normal animals; proven heterozygotes were found that were definitely intermediate between the two homozygous genotypes, and mature profiles were attained by 30 months of age (Gregory *et al.*, 1951, 1952). As more profiles were accumulated, it became evident that there were several distinct patterns of head profiles (figs. 1 and 2 and 7–22, pp. 423–424) and also that there were differences associated with sex. Bulls proved more favorable

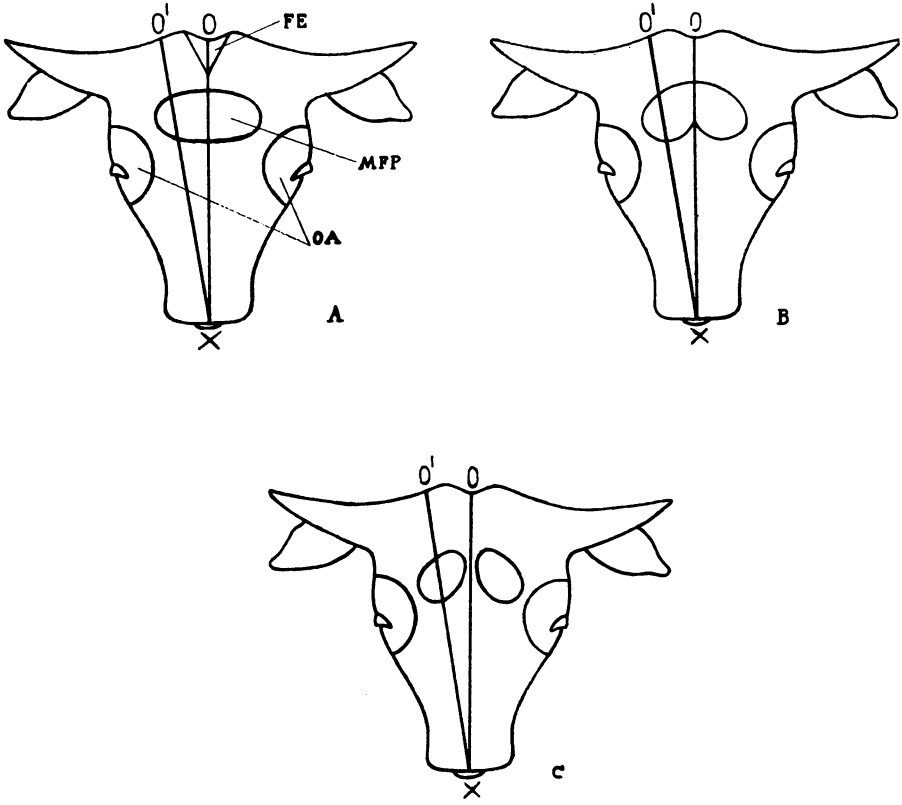


Fig. 1. Diagram of the bovine head showing the position of the profiles taken and the nature of the mid-forehead prominence (MFP), commonly referred to as the supra orbital region. The median profile is obtained along the line OX, the off-center profile along the line O¹X. The frontal eminence (FE) varies considerably in elevation and the length it extends along the frontal suture. The orbital arches vary greatly in extent. The mid-forehead prominence (MFP) caused by the dwarf gene is consistently manifest in heterozygous bulls but assumes several characteristic forms, dependent upon other factors. A common form is an elevation of the whole mid-forehead region as in A. Often a groove along the frontal suture in the anterior portion of MFP results in a kidney-shaped mid-forehead prominence as in B. If the groove extends a sufficient distance toward the poll, the mid-forehead prominence is separated into two distinct lobes (C). With experience, all three types may be recognized by palpation.

material for detecting the expression of the dwarf gene because the basic head form does not mask the dwarf gene to the same extent as in cows, and the genotypes of a sufficient number of homozygous normal bulls could be established by progeny tests. Attention was, therefore, directed almost exclusively to the study of bulls. The profiles used are from bulls of breeding age. The actual age range at the time of profiling is from 15 months to 13 years. The first task was to attempt to classify the head profiles into logical types consistent with basic anatomical structures and development patterns independent of the dwarf gene. Furthermore, it was necessary to relate the different parts of the profile to specific bones and structures of

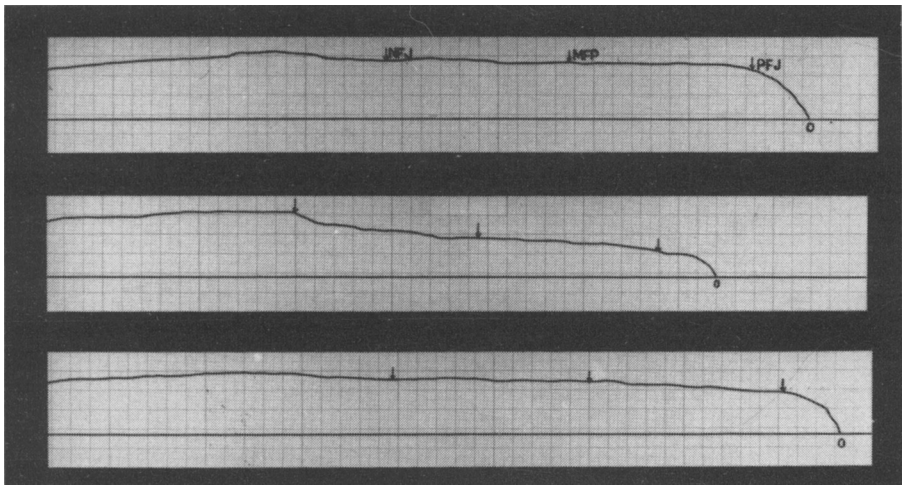


Fig. 2. Examples of Class I median head profiles from bulls of unknown genotype. The point O at the right is at the extreme posterior part of the skull, or poll, and the end of the profile at the left is approximately 6 cm posterior to the tip of the nose. The point at the approximate location of the parietal frontal juncture is indicated by PFJ. The approximate point on the profile at which the dwarf gene exerts its maximum upward thrust is called the mid-forehead prominence and is referred to as the MFP. The approximate location of the nasal frontal juncture is indicated by the symbol NFJ. The characteristic of the Class I head is a lack of longitudinal dish.

the skull. It was also necessary to determine whether the profile reflected basic differences in anatomical bone structures or superficial differences of the skin and subcutaneous tissue that had little significance. This was checked by comparing the profile of the animal before slaughter with the profile obtained after the skin and adhering tissue were removed from the head. There was substantial agreement between the profile of the living animal and that of the skull. One noteworthy difference is that curves were more abrupt after the skin was removed, showing the sharp angles characteristic of skeletal features without the modifying effect of the integument and subcutaneous tissue.

After it was realized that the dwarfism involved was a cretin type, that a marked bulging of the frontal bones was one of the outstanding characteristics of the cretin syndrome, and that the modification of the frontals was well understood by descriptive and experimental anatomists, the problem of

diagnostic points become more clearly defined. Thus it was assumed that it might be possible to locate points on the median profile that would have diagnostic value in separating dwarf-carrier and dwarf-free genotypes. It appeared that the points offering the greatest diagnostic value should be: (1) the nasal frontal juncture, (2) the parietal frontal juncture, and (3) the point on the frontals at which there is a maximum upward thrust. The primary objective was to differentiate between the heterozygous and homozygous normals.

The term "basic head profiles" refers to the type of profiles that naturally occur when the dwarf gene is absent from the genetic complex. Thus basic head profiles would be subject to variations from all genetic, environmental, and age effects, except the influence of the dwarf gene. The more important diagnostic points used for differentiating between heterozygous and homozygous normals are also used for classification of the basic head types. Since the profile is reproduced on millimeter paper, all diagnostic points are easily located.

The definition of diagnostic points, the means of locating them, and the symbols used to designate them apply to the median profile only.

Symbols and Terms Used to Designate the Diagnostic Points

Base Line—The lowest point on the graph paper at which the pen can write.

O —The origin or beginning of the profile at the poll. This is the point at which the profile intersects the base line.

PFJ —The approximate location of the juncture of the parietal bone with the frontal bones along the median profile. This is determined by taking the point 3 cm toward the nose from O. A study of skulls and skin thickness led to this method of locating the point.

MFP —The approximate location in the region of the mid-forehead along the median profile at which the dwarf gene, if present, exerts its maximum effect in causing a mid-forehead prominence. Since heads with extreme dish tend to mask the effect of the dwarf gene, the MFP point is determined arithmetically by the formula, $O + \frac{HL}{4}$. Thus in a head 48 cm long the MFP would be the point along the profile 12 cm in front of O.

NFJ —The approximate location of the juncture of the nasal bones with the frontal bones along the median profile. This point is determined mechanically and is the same distance anterior to MFP that PFJ is posterior to MFP. Thus MFP is halfway between NFJ and PFJ. Since the nasal-frontal juncture, mid-forehead prominence, and parietal-frontal juncture are used often in this report, in order to conserve space each may be referred to as NFJ, MFP, and PFJ, respectively. When favorable anatomical material is available, some of these diagnostic points may be located more accurately if desirable. In the system followed, PFJ, MFP, and NFJ are located objectively, and all genotypes and basic head types are subject to identical treatment.

The term *longitudinal dish* used in the classification of the basic head types needs definition. Longitudinal dish is defined as any concavity that may be manifest on the median profile in the region of NFJ or posterior to it but in front of the MFP. This concavity may be caused by the elevation of the nasal bones toward the nose, coupled with the elevation of the frontals and/or parietals toward the poll. The frontal bones themselves may be curved to effect most of the dish. The dish described is not caused by the dwarf gene. When the dwarf gene is present, however, it modifies the dish. *Before a head is classified as dished the elevation of MFP or the frontals or parietals posterior to the MFP should exceed the lowest point of the concavity by 4 mm.*

The diagnostic points PFJ, MFP, and NFJ should be located to the nearest millimeter and indicated on the profile. All vertical differences between diagnostic points should be to the nearest millimeter.

The Types of Basic Head Profiles

A. There is no longitudinal dish in the median profile.
   Class I.

B. There is longitudinal dish in the median profile.
   Class II. The vertical level of PFJ is less than 1 cm higher than NFJ. (PFJ may be lower than NFJ.)

C. The vertical level of PFJ is 1 cm or more higher than NFJ.
   Class III.

These basic head types are arbitrary classifications, but they are definitely related to specific anatomical features involved in the developmental process. The bones or bone structures that have the greatest effect upon the basic head types are: (1) the elevation of the nasals (either high or low), (2) the curvature of the frontal bones, and (3) the elevation of the frontal eminence (either high or low).

The characteristics of the head in which there is no dish (called an old-fashioned head by many breeders) are a high elevation of the nasal bones combined with straight or convexly curved frontals and usually, but not necessarily, a low frontal eminence. Thus the NFJ is the highest point or near the highest point in the profile. The most characteristic feature is a Roman nose.

There is considerable variation in heads that are dished. The elevation of the nasals may be high or low, the frontals may be concave or almost straight, and the frontal eminence may be high or low. Class III heads are definitely associated with a high frontal eminence and a marked curvature of the frontal bones, while nasals are usually (but not necessarily) low. The different types of head profiles are illustrated and defined in figure 2 and figures 7–22, pp. 423–424.

Identification of Genotypes from the Median Profile

The approximate frequences of the different basic-profile types in bulls of proven genotype, which are mostly herd sires, are Class I, 5 per cent, Class II, 70 per cent, and Class III, 25 per cent. Class I is a type that many breeders have been selecting against. In the herds sampled, the incidence of

Class I bulls was higher in commercial herds. As yet no attempt has been made to separate bulls with Class I heads into heterozygous and homozygous normal genotypes. The accumulated sample consists of less than a dozen that are proven and only one that is homozygous normal.

Finding a sufficient number of bulls proven by progeny test to be homozygous normal was a greater problem than was anticipated. There was rarely a question regarding the genotype of a bull when the owner stated that he was a dwarf carrier. Even though there might be an occasional error, the natural conservatism of breeders acted as a safeguard against the incrimination of a sire with insufficient evidence. This conservatism, however, enhanced the probability of classifying heterozygotes as homozygous normal if the proper precautions of progeny-testing were not observed. Furthermore, since the dwarf gene had been in the stock a long time and was widely disseminated, many herds and animals were potential carriers even though the owner was unaware of the fact. It soon became evident that homozygous normal sires could not be reliably selected without employing the progeny test in some manner.

All proven bulls, both heterozygous and homozygous, are included in this study. Since proven homozygous animals are rare, the status of the proving or the reasons for assuming homozygosity for the animals used to determine the diagnostic points, to make the key, and to calculate the discriminant functions are assembled in table 4. All of these bulls used as models for homozygotes were selected late in 1950 or the first half of 1951. The profiles of the limited number of proven homozygotes were unique. During this early period the characteristics of certain types of profiles manifested by some heterozygotes became well recognized, and predictions that several of these were heterozygous proved correct without error. The success of these early predictions coupled with the fact that dwarf-carrier bulls were definitely rejected in the selection of the individuals composing the model for homozygotes (table 4) makes it clear that during this early period of the investigation some heterozygotes manifested head profiles so distinct that these dwarf-carriers could be recognized with what proved to be unerring accuracy. The status with regard to progeny tests of the homozygous normal bulls used to check the key and discriminant functions is shown in tables 5 and 10. In addition to these critical animals, other bulls that are partially proven but below the 10 per cent level, or that have sired large numbers of progeny in herds that have never had dwarfs, are used as a check. Where these are used, they are clearly indicated. One herd that has never had dwarfs and that has been subjected to sufficient breeding tests to indicate that the population has a low frequency of the dwarf gene—if it is not actually dwarf-free—is included in this analysis, even though some of the bulls have not been progeny-tested. This group is referred to as the M check. Data collected on individual bulls in other herds in which there are no progeny tests and that have never been proven are not considered in the analysis. The data used in this study were processed by April 1, 1953.

The general practice recommended is to use only animals in which there are two median profiles in good agreement. When properly checked, this is conducive to careful work in the field and reduces errors in the predic-

tion of genotypes. Many of the data used in this paper, however, are based upon one profile. Since all the "homozygous" normal bulls used to make the key and calculate the discriminant functions were not proven, their use is limited. They were used as a model for homozygotes, to be checked against homozygotes proven by progeny tests.

KEY FOR DIFFERENTIATING THE GENOTYPES IN CLASS II AND CLASS III

B. There is longitudinal dish in the median profile.
Class II. The vertical level of PFJ is less than 1 cm higher than NFJ.
1. Heterozygous or predominantly heterozygous.
a. The vertical level of MFP is 6 mm or more higher than PFJ. Class II 1 a.
b. The vertical level of MFP is from 3 mm to less than 6 mm higher than PFJ, and the vertical level of MFP is 6 mm or more higher than NFJ. Class II 1 b.
c. The vertical level of MFP is from 3 mm to less than 6 mm higher than PFJ, but the vertical level of MFP is less than 6 mm higher than NFJ. Class II 1 c.
d. The vertical level of MFP is less than 3 mm higher than PFJ, but the vertical level of MFP is 8 mm or more higher than NFJ. Class II 1 d.
e. The vertical level of MFP is less than 3 mm higher than PFJ, but the vertical level of MFP is 6 mm or more, but less than 8 mm, higher than NFJ. Class II 1 e.
2. Homozygous normal or predominantly homozygous.
a. The vertical level of MFP is less than 3 mm higher than PFJ, and the vertical level of MFP is less than 6 mm higher than NFJ. Class II 2.

C. The vertical level of PFJ is 1 cm or more higher than NFJ.
Class III. The vertical level of PFJ is 1 cm or more higher than NFJ.
1. Heterozygotes or predominantly heterozygous.
a. The vertical level of MFP exceeds NFJ by 13 mm or more. Class III 1 a.
b. The vertical level of MFP exceeds NFJ by 8 mm to 12 mm. Class III 1 b.
2. Homozygous normal or predominantly homozygous.
a. The vertical level of MFP is less than 8 mm higher than NFJ. Class III 2 a. (In bulls five years of age or older, there are modifications along the suture that may slightly disrupt these relationships, but the discriminant functions differentiate them more efficiently.)

Predictions of genotype for dwarfism of bulls from 15 months of age or older, based upon the diagnostic points of the median head profile, have been in progress for over two years. The actual error has been less than 5 per cent for Class II and III bulls, the types upon which predictions were made. The physical basis for successful prediction is shown in figures 7–14

(p. 423) for Class II heads and figures 15–22 (p. 424) for Class III heads. It is evident that the dwarf gene in the heterozygous state affects the relationship of MFP with both NFJ and PFJ. A study of figures 3, 4, 5, and 6 indicates that there are definite profile patterns. This is clearly illustrated in heads of Class II 1 d. Note the distribution of MFP minus PFJ (fig. 3) and the distribution of MFP minus NFJ for the same heads (fig. 4). The whole population for profiles of both Classes II and III may be made up of several distinct populations. It is now understandable why it is possible to distinguish dwarf-carrier and dwarf-free genotypes by means of the key. With but six exceptions, all Class II 1 heterozygotes can be differentiated from the Class II 2 homozygous normals. There is one slightly atypical heterozygote in Class III that overlaps with the homozygotes. These seven exceptional heterozygotes that overlap with homozygous normals and the one homozygous normal (figs. 5 and 6) that overlaps with heterozygotes will be considered later when factors affecting the median profile are discussed. The point to be emphasized is that there is a definite physical basis for differentiating between heterozygous and homozygous normal genotypes from the simple relationships of the three diagnostic points of the median profile. The predictive value can be made with high accuracy by applying the key, based upon the distributions shown in figures 3, 4, 5, and 6.

Even though the key is effective in differentiating between dwarf-carrier and dwarf-free bulls, it has limitations. There is no clear-cut demarcation between Class II and Class III heads. Since the vertical relationships of MFP with both NFJ and PFJ are diagnostic, the key does not permit combining both of these characteristics, and any others that may be diagnostic, into one expression such as a discriminant function. The method of Goulden (1952) was used in calculating the discriminant functions. Various combinations of the following four variables were used in these calculations.

X_1 = the vertical level of MFP minus the vertical level of NFJ in mm.

X_2 = the vertical level of MFP minus the vertical level of PFJ in mm.

$X_3 = X_1 + X_2$

X_4 = cephalic index of $\frac{\text{head length}}{\text{head width}}$

When MFP is higher than either NFJ or PFJ the difference is a plus value. When MFP is lower than either of the other points, the difference is a minus value. When PFJ is higher than NFJ, the difference is a plus value. When PFJ is lower than NFJ, the difference is a minus value.

Several different discriminant functions have been calculated, which, when applied, show a differentiation of genotypes that separate reasonably well the heterozygous and homozygous individuals into distinct groups. A discriminant function was computed for the Type II profiles. A key group (numbers 1 to 9, inclusive, table 4) of homozygous normals was used to compute the function, and another group was used for a check. A similar procedure was followed for Type III profiles. The animals used as models for homozygotes are numbers 10 to 15 inclusive (table 4). In both cases, the discriminant function $1.15X_1 + X_2$ was obtained. The distribution of heterozygous and homozygous normal bulls based upon this discriminant function is shown in figure 23.

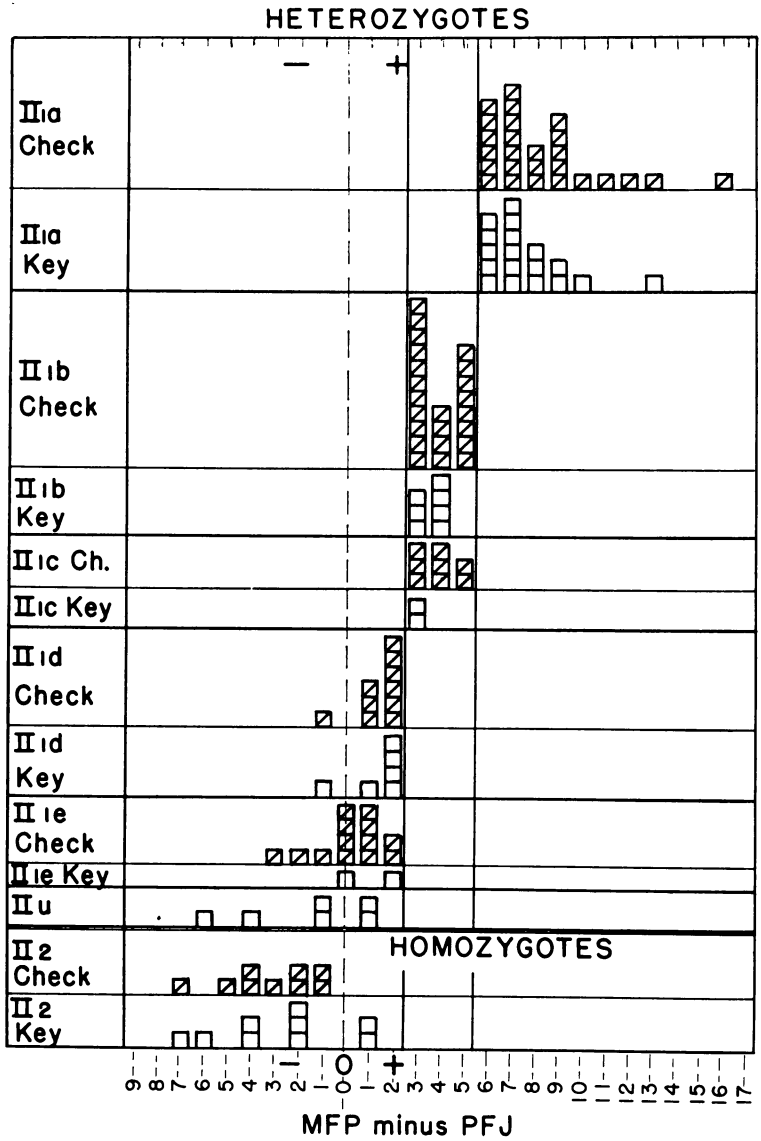


Fig. 3. Histogram showing the frequency distribution of differences in vertical level between MFP minus PFJ of heterozygous and homozygous normal bulls of Class II. These are the same animals shown in figure 4. All animals in Classes II 1 a, II 1 b, II 1 c, II 1 d, II 1 e, and II u are proven heterozygotes. Animals classed as II 2 are proven homozygous normal or are from lines in which the bulls are partially proven from herds in which the frequency of the dwarf gene is known to be low.

Classes II 1 a, II 1 b, and II 1 c are completely separated from the homozygous normals of Class II 2. Heterozygotes of subclasses II 1 d and II 1 e are not differentiated by this diagnostic characteristic but by MFP minus NFJ (see fig. 4). The ones in II u are not differentiated by either of these diagnostic characteristics (see text, pp. 428–432 for explanation).

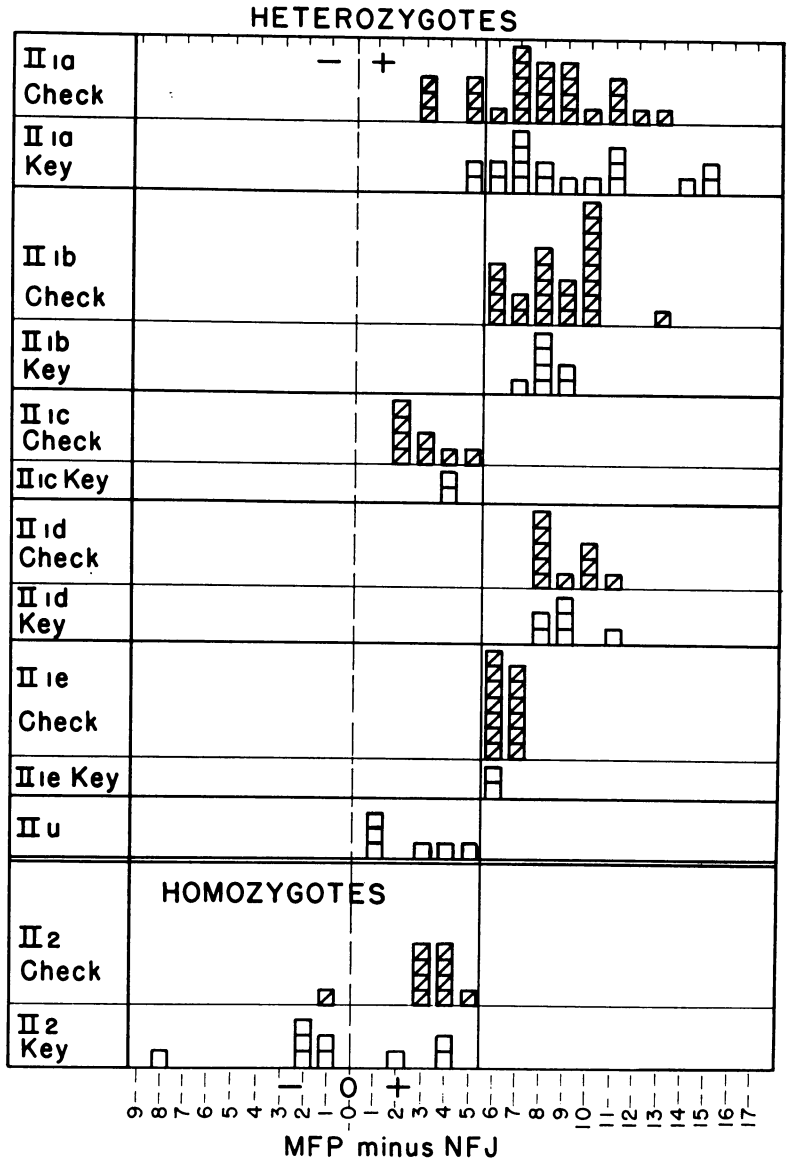


Fig. 4. Histogram showing the frequency distributions of heterozygous and homozygous normal bulls of Class II for the diagnostic characteristic MFP minus NFJ.

These are the same animals shown in figure 3. Note that this diagnostic characteristic does not completely separate all that fall into Class II 1 a, as does the characteristic MFP minus PFJ; Class II 1 b is separated from homozygotes. (Both 1 a and 1 b are also separated by MFP minus PFJ). Class II 1 d heterozygotes are completely separated from homozygotes, as is Class II 1 e. The six II u animals are not differentiated.

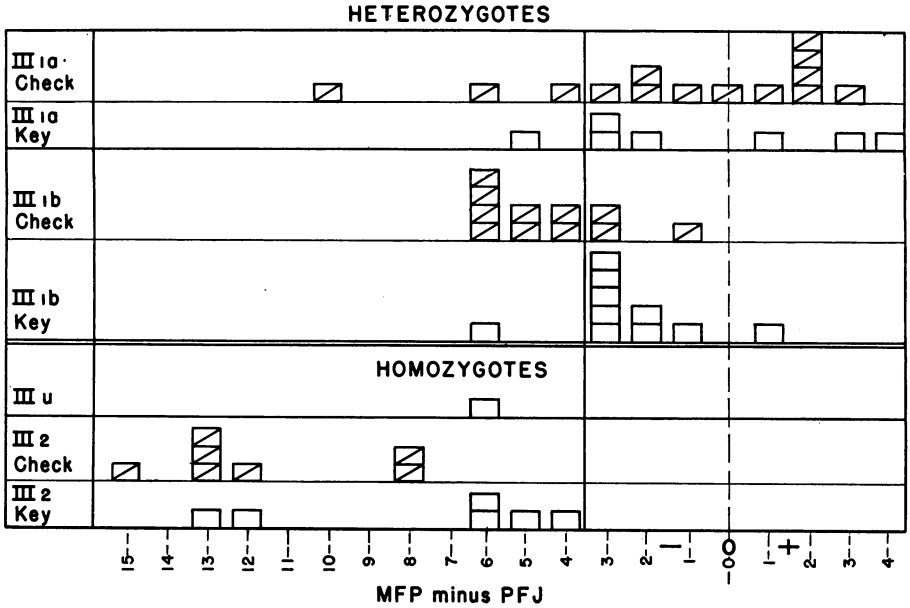


Fig. 5. Histogram showing the frequency distributions of difference in vertical level between MFP minus PFJ of heterozygous and homozygous normal bulls of Class III. These are the same animals shown in figure 6. All animals in Classes III 1 a and III 1 b are proven heterozygotes. All animals in Class III 2 are proven homozygous or are from lines in which the frequency of the dwarf gene is known to be low. In Class III, heterozygous and homozygous normals have different distribution values although there is a considerable overlap.

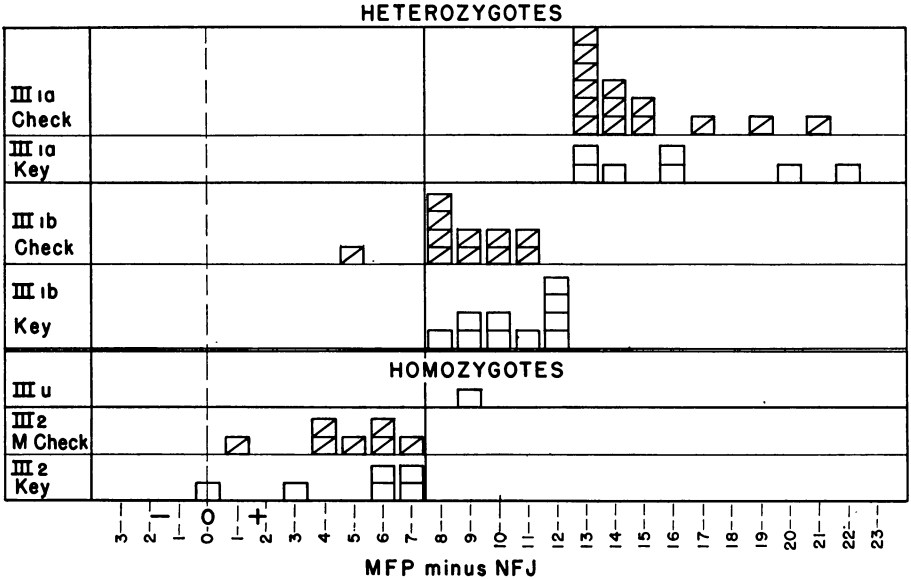
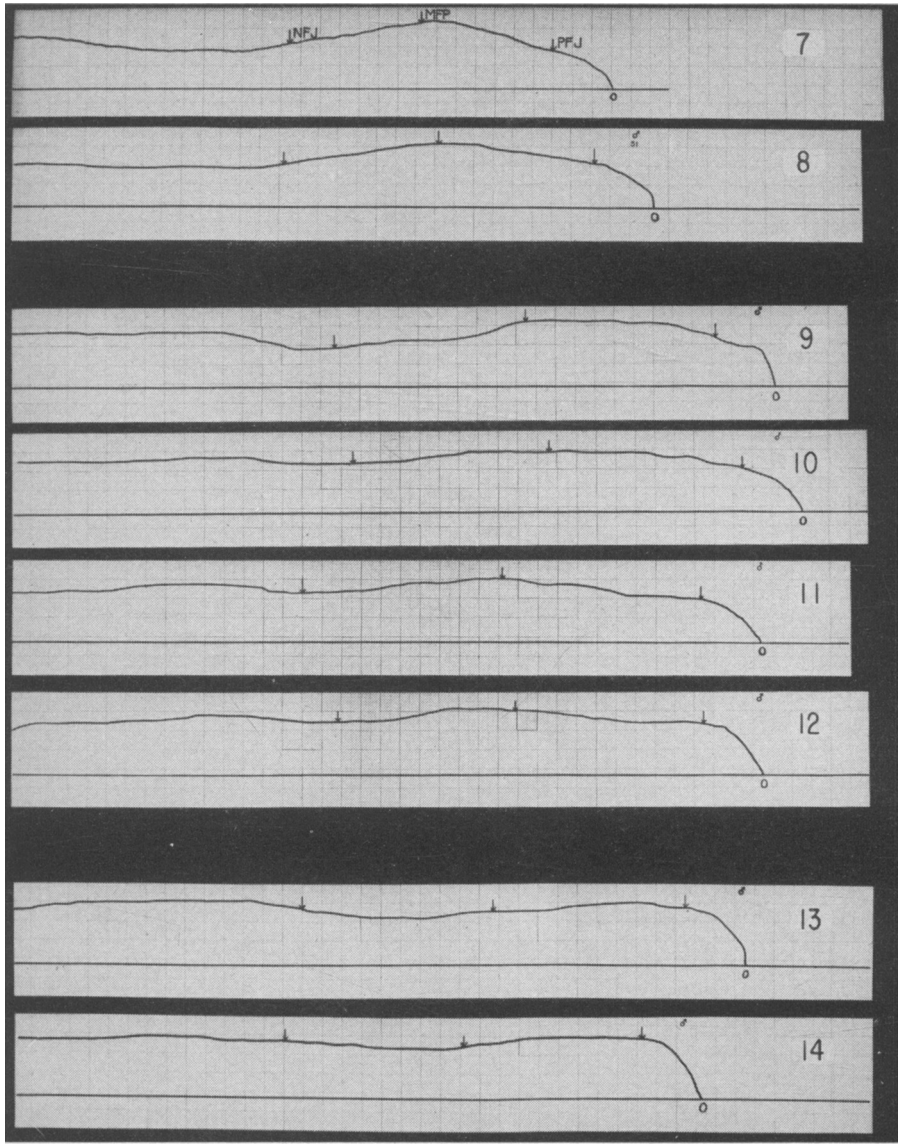
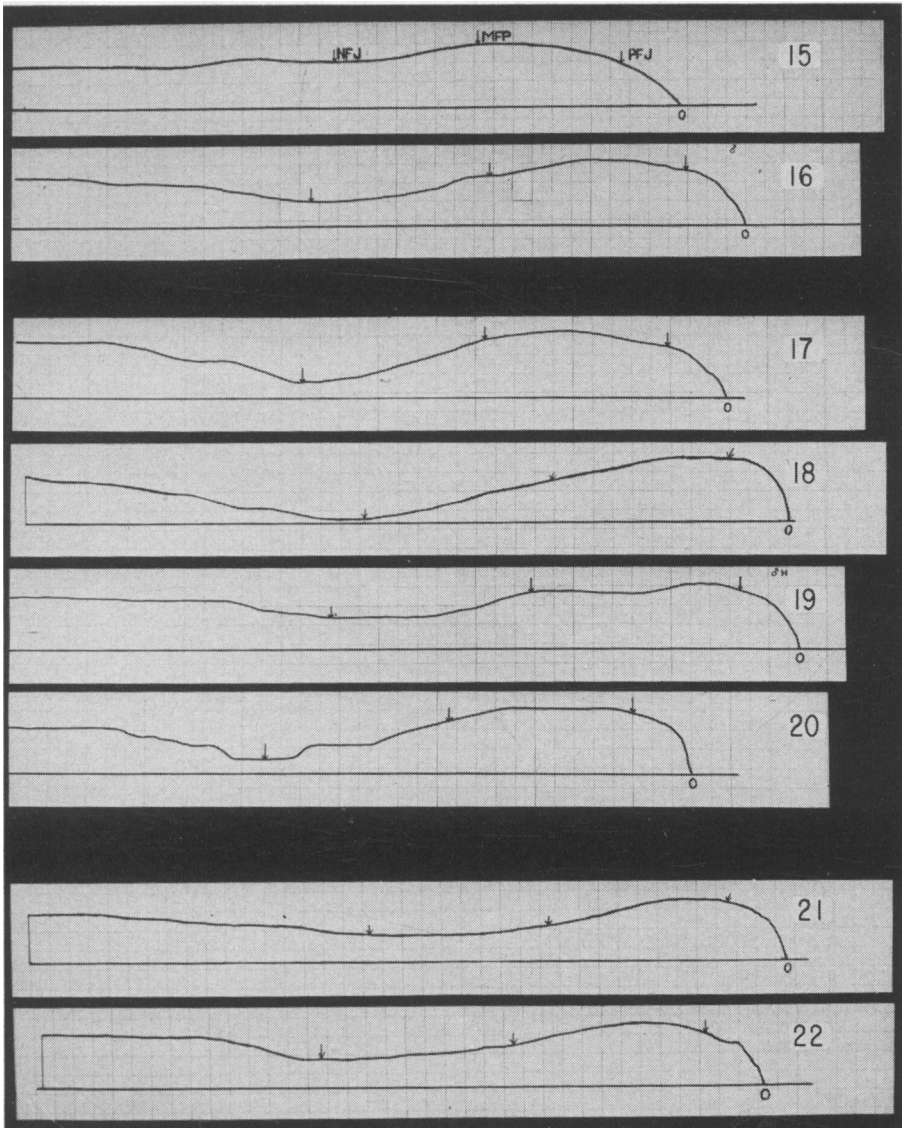


Fig. 6. Histogram showing the frequency distributions of the difference in vertical level between MFP and NFJ of the same Class III animals shown in figure 5. With but two exceptions this characteristic completely separates the two genotypes (see text, pp 428–432 for explanation and discussion).



Figs. 7–14. Characteristic median head profiles of dwarf and mature heterozygous and homozygous normal bulls that possess relatively flat heads (only slightly curved frontal bones with a medium elevation of both the nasal bones and frontal eminence). The O point is at the poll. The dwarfs (figs. 7 and 8) manifest the characteristic marked bulge in the mid-forehead (supra orbital) region. Typical profiles of proven homozygous normal bulls are shown in figures 13 and 14; note that they completely lack the prominence in the mid-forehead region that is characteristic of dwarfs.

Figures 9, 10, 11, and 12 are profiles of bulls proven to be heterozygous for the dwarf gene. Note that they are intermediate between the two homozygous genotypes.



Figs. 15–22. Characteristic median head profiles of a dwarf and heterozygous and homozygous normal bulls in which there is an extreme concavity of the frontal bones.

The profile of the dwarf (fig. 15) showing the typical bulge of the frontals, may be compared with the profiles of the other genotypes. Typical profiles of homozygous normal bulls are shown in figures 21 and 22. Note that a mid-forehead prominence is completely lacking in these bulls.

Figures 16, 17, 18, 19, and 20 are from heterozygous bulls. Even though the curvature (concavity) of this basic head type tends to mask the effect of one dwarf gene, the heterozygote is intermediate when compared with the two homozygous genotypes. All methods of differentiating between heterozygous and homozygous normals are based primarily or exclusively upon the difference in vertical relationships of NFJ with MFP and MFP with PFJ.

With an exception in Class 6, the homozygotes and heterozygotes used to calculate this discriminant function are completely separated. The animals used to check the function follow similar distribution patterns in both genotypes. The F test (Snedecor, 1940) is significant at higher than the 0.01 per cent level, and the conclusion is that this discriminant function differentiates reasonably well dwarf-carrier and dwarf-free bulls in the population studied. Since the separation of genotypes is distinct but hardly complete, if judicious selection is practiced in the overlapping zone, it should be possible to select effectively against heterozygotes in the overlapping range.

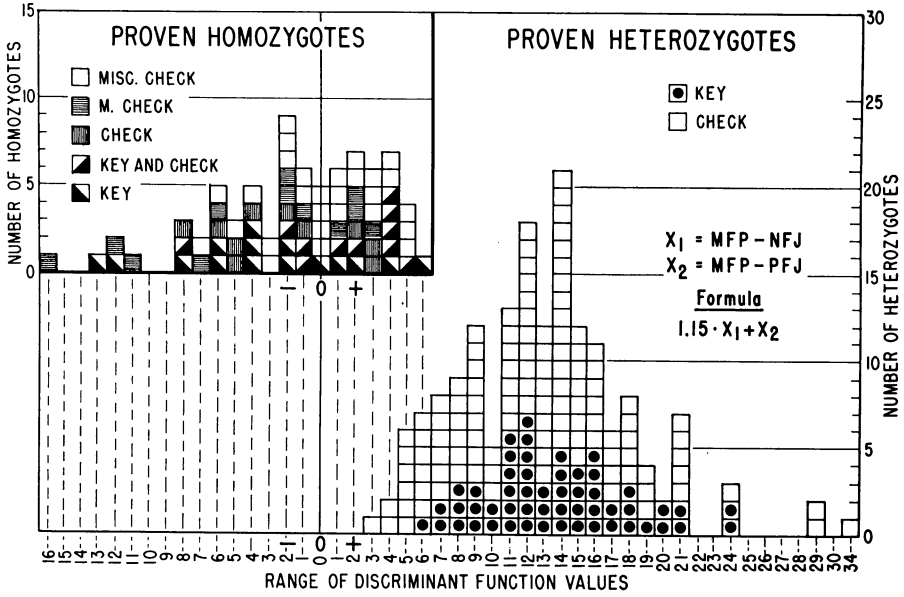


Fig. 23. A histogram showing the distribution of mature bulls proven by progeny tests to be dwarf-carrier and dwarf-free when the discriminant function $1.15X_1 + X_2$ is applied. The animals used to calculate the discriminant function and those used to check it are indicated. These are the same animals used in figures 24, 25, and 26.

In the computations of the subsequent discriminant functions, the Type II and Type III profiles were combined; the heterozygous animals used in the first discriminant function and all proven homozygous normal animals available at the time (key and key and check, figs. 23, 24, 25, and 26) were used to obtain constants that should be more accurate.

Discriminant function 2 employs characteristics X_1, X_2, and X_3. The computed function is $-1.77X_1 + X_2 + 1.3X_3$. When the second discriminant function is applied to the homozygous and heterozygous animals used to calculate this function, they are completely separated (fig. 24). The distributions of the animals used to check the function are similar to those used for the computation, and there is complete separation between the two genotypes on all except class 2. Furthermore, the F test indicates that this second formula should give far greater discriminating power than the first. This is evident when figures 23 and 24 are compared. Professor Wright kindly pointed out

that since X_3 is related to both X_1 and X_2, the formula $-1.77X_1 + X_2 + 1.3X_3$, as originally used, can be reduced to $1.57X_1 + X_2$. The actual difference, then, between discriminant functions 1 and 2 is in the number of animals used to

TABLE 4

STATUS WITH RESPECT TO THE DWARF GENE OF BULLS USED AS A MODEL FOR HOMOZYGOUS NORMAL TO DETERMINE DIAGNOSTIC POINTS ON THE PROFILE AND DEVELOP THE KEY AND THE FIRST DISCRIMINANT FUNCTION

Code No.	Profile classification	Status of progeny test
1	Dwarf-free	Proven higher than 1 per cent level
2	Dwarf-free	Proven at 5 per cent level
3	Dwarf-free	The breeder in charge considered this herd to be free from the dwarf gene because it had never produced a recognizable dwarf. These two bulls are partially progeny-tested but below the 10 per cent level. Two other bulls related to these but from an outcross made 10 years before were rejected as models for homozygotes because their profiles resembled heterozygotes. Within 18 months both rejected bulls sired dwarf calves
4	Dwarf-free	
5	Dwarf-free	Both from line 1 of the Miles City Station. Average coefficient of inbreeding in 1948, 15.9. No dwarfs have occurred in the line, and they were considered by the station to be dwarf-free. Other bulls from this station were rejected because their profiles did not agree with the profiles of proven homozygotes. One of those bulls in the rejected class sired a dwarf in the 1953 calf crop
6	Dwarf-free	
7	Dwarf-free	Proven higher than 1 per cent level
8	Dwarf-free	All sired by a bull, No. 11 of this table, that was used for many years in the California Station herd and never sired a dwarf. He produced 8 normal calves and no dwarfs, from sire-daughter matings, and there were other normal progeny from irregular test matings. His proving is below the 10 per cent level. The profiles of all these bulls are similar to proven homozygous-normal bulls of the same classification. It is assumed that some of the cows in the California Station herd are heterozygous for the dwarf gene since some of their sons manifest profiles characteristic of heterozygotes. Furthermore, some of these cows are related to proven heterozygotes
9	Dwarf-free	
10	Dwarf-free	
11	Dwarf-free	Sire of bulls 8, 9, and 10 above
12	Dwarf-free	Proven at 7 per cent level
13	Dwarf-free	Proven higher than 1 per cent level. The owner thought that three other bulls from this herd should be free from the dwarf gene. These three were rejected, however, because all possessed profiles characteristic of heterozygotes; all three have since proved heterozygous
14	Dwarf-free	Proven higher than 1 per cent level
15	Dwarf-free	Not proven but never sired a dwarf; selected because his profile was similar to proven homozygotes

make the computations. Since a larger sample of animals was used in calculating the latter formula, the constant 1.57 should be nearer the true value than the constant 1.15 found in the first formula. When the formula $1.57X_1 + X_2$ is applied to animals shown in figure 24, the distributions shown in figure 25 are obtained. This function separates the two populations quite well. Even

in the overlapping classes it should be possible to state the probability that an unproven animal is homozygous or heterozygous. This formula should replace the ones used in figures 23 and 24.

Since the cephalic index of head length over head width $\left(\frac{HL}{HW}\right)$ is known

TABLE 5

STATUS WITH RESPECT TO THE DWARF GENE OF THE HOMOZYGOUS BULLS USED TO CHECK THE KEY AND THE FIRST DISCRIMINANT FUNCTION*

Code No.	Profile classification	Status of progeny test
16	Dwarf-free	Proven at 2 per cent level
17	Dwarf-free	Proven higher than 1 per cent level
18	Dwarf-free	Proven at 10 per cent level
19	Dwarf-free	Proven at 5 per cent level
20	Dwarf-free	These bulls were used in a herd in which there was a high frequency of the dwarf gene. The way the records were kept it is difficult to state the absolute probability at which they may be considered homozygous. Each of these bulls had sired about 150 normal calves and no dwarfs. The owner considered them proven free from the dwarf gene and was mating them accordingly. They are probably proven around the 5 per cent level or higher
21	Dwarf-free	
22	Dwarf-free	
23	Dwarf-free	Proven higher than 1 per cent level
24	Dwarf-free	Proven at 5 per cent level
25	Dwarf-free	Proven at 2 per cent level
26	Intermediate range	Apparently proven much higher than 1 per cent level, but the records were poor
27	Dwarf-free	M check. All of these bulls are from one herd that has never produced a dwarf. If the dwarf gene is present in the herd, the frequency is low. The cows of this breeding have produced approximately 300 normal calves and no dwarfs when mated to heterozygous bulls. Numbers 16 and 17 in this table are of this breeding. Several bulls of this line are being progeny-tested
28	Dwarf-free	
29	Dwarf-free	
30	Dwarf-free	
31	Dwarf-free	
32	Dwarf-free	
33	Dwarf-free	
34	Dwarf-free	
35	Dwarf-free	
36	Dwarf-free	
37	Dwarf-free	
38	Dwarf-free	

* Numbers 16 to 25, inclusive, were used in the calculation of the discriminant functions shown in figs. 24, 25, and 26.

to be influenced by the dwarf gene, this characteristic was used to calculate another discriminant function in conjunction with characteristics X_1 and X_2. The same animals used in the second function (fig. 24) were used in the calculation of the constants of this discriminant function, which is $-7.45X_1 - 4.83X_2 + X_4$. The distributions when this function is applied to the animals

used for the calculation of the function and the checks are shown in figure 26. Here again the distributions of key and check animals are in good agreement, and the function has marked ability to differentiate the dwarf-free and dwarf-carrier genotypes. The F test indicates that it is significant at higher than the 1 per cent level. It is assumed from the distributions of the two genotypes in the overlapping zone that it is possible by means of judicious selection to pick a high percentage of dwarf-free animals in the overlapping

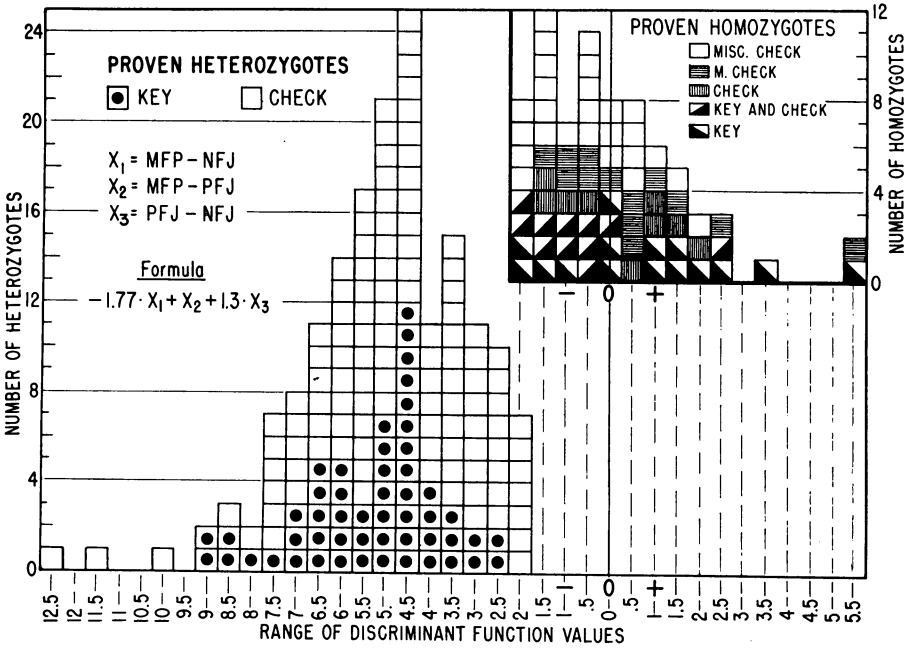


Fig. 24. A histogram showing the distribution of mature bulls proven by progeny tests to be dwarf-carrier and dwarf-free when the discriminant function $-1.77X_1 + X_2 + 1.3X_3$ is applied. These are the same animals shown in figures 23, 24, 25, and 26. However, the proven homozygous normal animals used to check the function in figure 23 (key and check) are combined with those used to calculate this function in this figure. This was done to obtain truer constants. Another set of homozygotes is used to check this function.

area. Future study will have to determine the relative merits of the two functions shown in figures 25 and 26.

It seems worthwhile to check in heterozygotes the types of profiles as classified in figures 3, 4, 5, and 6 by the key with those that overlap with homozygous normal when the discriminant functions are applied. The heterozygotes that overlap are from classes II 1 e, II 1 c, II 1 d, and III 1 b. These classes were originally set up because it was suspected that occasionally heterozygotes of these characteristics might intergrade with some homozygous normals.

Attention will now be directed to the six heterozygotes that cannot be differentiated by the key or by any of the discriminant functions (these are not shown in figures 23, 24, 25, and 26 but are shown in figures 3 and 4) and

the heterozygotes that are differentiated by the key but overlap on one or more discriminant functions. Perhaps all the discrepancies can be accounted for by known factors that have been found to affect the median profile. The basic head type upon which the dwarf gene operates is of prime importance. Heterozygotes that have a low frontal eminence and little curvature of the frontal bones can be readily identified from the profile (figures 7–14). When the frontal eminence is high and there is a marked curvature (concavity) of

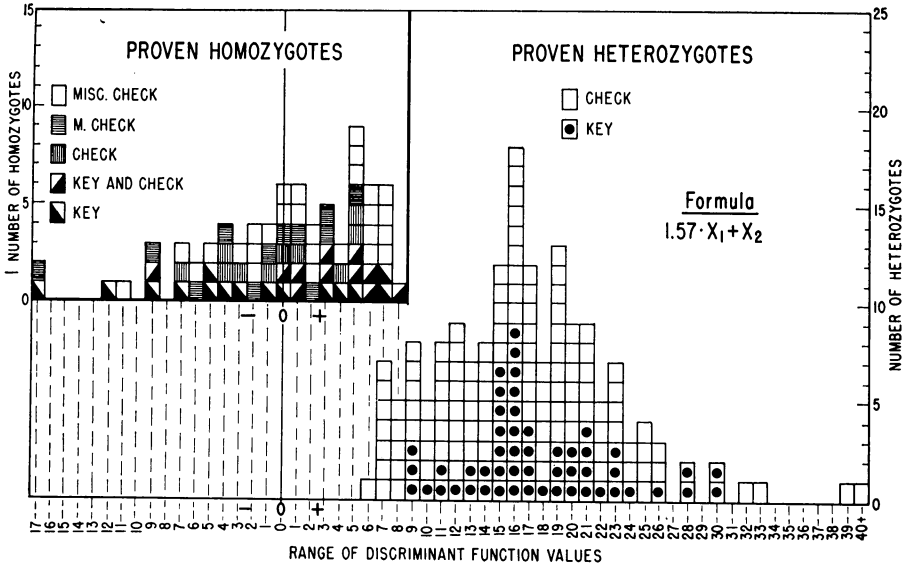


Fig. 25. A histogram giving the distribution of the bulls shown in figures 23 and 24 when the discriminant function $1.57X_1 + X_2$ is applied. This is the equivalent of the formula $-1.77X_1 + X_2 + 1.3X_3$ shown in figure 24 (see p. 428). This formula is to supersede both the formulas used in figures 23 and 24.

the frontal bones, the general head shape tends to mask the expression of the dwarf gene when it is present (figs. 15–22, p. 424). The elevation of the nasal bones (either high or low) may also be a factor, although if it is there is probably some interaction between the positions of the nasals and the frontals.

The wedge-shaped elevation usually found along the frontal suture posterior to the MFP point and the features of the frontal suture in the region of MFP have considerable influence on the median profile since both have a marked effect upon the MFP caused by the dwarf gene. The nature of the MFP can usually be determined by palpation after one becomes experienced and understands what to look for, although in certain head types it is often well masked. At least three types of mid-forehead prominences can be recognized by palpation. One is a type in which the prominence is somewhat oval and rounded (fig. 1A). If there is a groove along the frontal suture anterior to the MFP point, the MFP appears kidney-shaped (fig. 1B). If the groove extends toward the poll to divide the MFP into two completely separate lobes, the median profile need not show a prominence in hetero-

zygotes. The heterozygote (III 1 b) that does not conform in figure 6 is of that type. The bilobed MFP was first discovered in this animal. It has been definitely recognized in two of the six animals that do not conform in figure 4. The other four animals that do not conform were examined before the bilobed MFP was discovered and the palpation technique developed. It is suspected that these last four that do not conform also had a grooved frontal suture that made the MFP bilobed. The "off center" profile taken

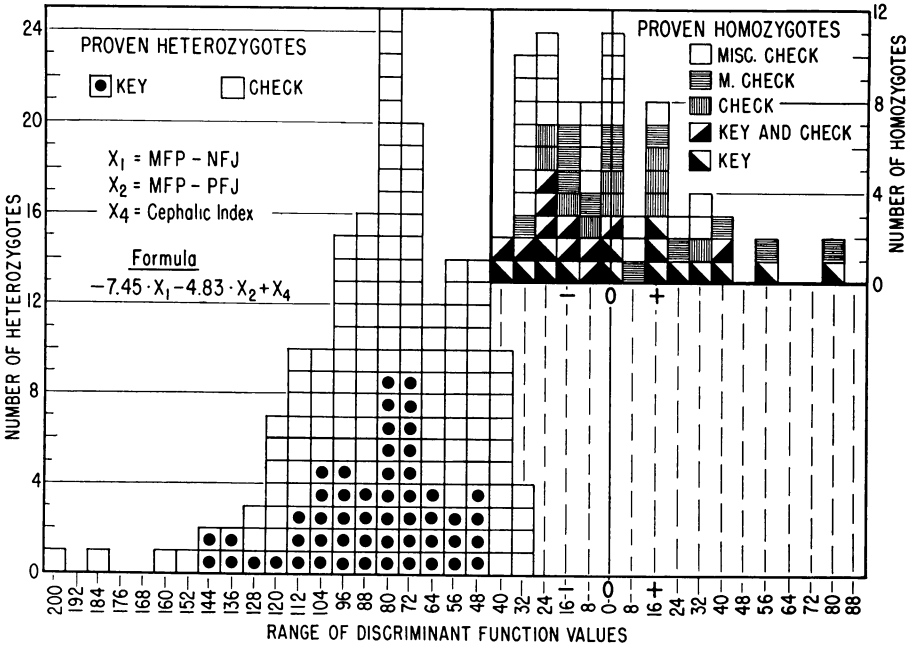


Fig. 26. A histogram showing the distribution of mature bulls proven by progeny tests to be dwarf-carrier and dwarf-free when the discriminant function $-7.45X_1 - 4.83X_2 + X_4$ is applied. The animals used here to calculate the discriminant function are those used also in figure 24.

along O^1X was developed to check the bilobed MFP, figure 1A. This "off profile" passes over one of the lobes. Since the off profile was developed after many of the critical data on proven homozygotes were collected, there have as yet been insufficient data to check the significance of the off profile as a diagnostic tool.

The characteristics of II 1 e profiles are a relatively high frontal eminence and little dish. It has recently been found that some have a groove along the suture in the region of the MFP. Some of these, at least, are related to the group that cannot be differentiated by the key or any of the discriminant functions. The III 1 b profiles that overlap on some of the discriminant functions are similar to the II 1 e in that they have a groove causing the MFP to approach a bilobed condition. This groove may also be a factor in the II 1 c heads that are not completely differentiated by one or more of the discriminant functions, although other relationships may also be involved. Thus,

when the profile does not conform to the characteristics typical of the genotype or falls into the overlap group of the two discriminant functions, other means—differentiation by palpation, diagnosis by the "off profile," or the use of the primitive key as originally used—may permit more positive genotypic classification. When large numbers of animals of proven genotype are available, it may be possible to state in terms of rather accurate probability the expected proportions of each genotype in each overlapping class.

TABLE 6

DISCRIMINANT FUNCTION $1.57X_1 + X_2$ APPLIED TO PROFILES TAKEN BY TWO OPERATORS USING TWO MACHINES

These profiles were taken in midwinter under adverse weather conditions in Wyoming, and show variations which can occur under unfavorable circumstances.

Animal Number	Operator A				Operator B			
	Profilometer I		Profilometer II		Profilometer I		Profilometer II	
	Profile		Profile		Profile		Profile	
	1	2	1	2	1	2	1	2
L1	7.14	8.71	7.14	7.71	9.28	11.85	12.42	9.28
L2	11.13	14.27	12.13	12.70	10.70	11.70	14.27	15.27
L3	18.56	19.84	19.70	16.13	21.27	21.84	18.27	22.27
L4	18.0	18.84	12.56	15.56	15.0	13.13	18.27	15.13
L5	10.42	10.42	15.0	13.42	15.56	14.0	14.0	13.42
L6	14.13	16.42	12.42	15.70	12.0	12.56	16.84	15.70
L7	12.85	13.42	12.85	15.0	17.56	18.56	15.42	13.85
L8	13.0	12.0	10.42	10.42	11.42	13.0	13.0	13.0
L9	20.27	20.27	20.70	23.55	20.27	23.84	23.27	20.13
L10	15.71	12.85	14.42	12.85	16.71	16.85	12.28	14.85
L11	3.28	3.28	1.14	2.71	3.85	2.28	2.28	2.28
L12	15.71	14.42	19.0	19.42	19.0	19.0	21.0	17.42
L13	12.57	10.0	16.57	15.0	9.39	10.43	11.86	10.86
L14	15.85	24.85	15.85	20.42	19.0	26.27	18.42	16.85
L15	3.85	2.28	2.85	1.28	4.85	4.85	4.85	4.85
L16	5.71	5.71	5.14	6.71	7.28	8.71	7.28	8.85
L17	15.42	18.0	22.56	17.42	18.42	15.85	15.85	13.28
L18	20.27	19.0	18.85	18.85	16.42	22.70	15.85	18.85

Studies of profile repeatability indicate that an experienced operator can take profiles with a high repeatability. Extreme care must be exercised when profiles are taken under adverse conditions, or when they are taken by inexperienced operators. When there are marked discrepancies, profile interpretations should not be attempted although a well-trained technician can often identify the more accurate profile.

Although the data are limited, enough are available to be certain that significant changes occur along the median profile during post-maturity. Just when the profile changes from the juvenile to the mature condition has not been determined, but it is some time between 12 (perhaps earlier) and 30 months of age. Many of the major changes in some animals have occurred by 15 months or earlier. Apparently when the mature profile is attained there is considerable stability until 5 or 6 years of age. Profound changes

are known to occur in the ages between 6 and 8 years and also between 11 and 13 years. The nature of the change appears superficially to be a thickening over the median frontal suture. These changes are sufficient to affect the relationship of the diagnostic points. The changes are of such a nature, however, that they would rarely modify the genotypic classification of an animal. It is assumed that the proven homozygous Class III bull that overlaps with the heterozygotes (fig. 6) on the key would at an earlier age have classified by the key as homozygous. Another old animal, probably homozygous, that was profiled at 11 years of age keyed homozygous and was in the homozygous group when all three discriminant functions were applied. When he was profiled two years later (with the same instrument) there were marked changes in the profile, although it had the same general features as the preceding one but classed as heterozygous by the key. On the discriminant functions he classed clearly as a homozygote on one and in the intermediate range on the others.

The check on instruments and operators obtained at the same time and on other bulls taken at different ages makes it certain that changes in head profiles do occur during post-maturity. An aged heterozygous bull was profiled twice, within an interval of 17 months. The second time, he was profiled with the same instrument originally used and also with a different one. Although the nature of the profile changed markedly, he keyed out as a carrier on all the profiles and on all the discriminant functions. This change of expression with age has been observed with other hereditary anomalies. In fowl, heterozygotes for the crested gene can be easily recognized in young birds, but the changes that occur in maturity make recognition more difficult (Fisher, 1935).

All the evidence indicates that the expression of the dwarf gene in mature bulls of popular breeding is of sufficient magnitude to differentiate with a high degree of accuracy between heterozygotes and homozygous normal genotypes. Although it is the most primitive method, the most accurate means of differentiation thus far encountered is by the key as originally used. Perhaps one reason for this is that in the key there is a slight variant in the use of the NFJ point, which was not used in any of the discriminant functions. When using the key, if there was a lower point on the profile toward the nose within 3 cm of the calculated NFJ, that lower point was used as the NFJ. This modified NFJ point was used only in the classification of less than a dozen animals, which characteristically had a low elevation of the nasal bones. The discriminant functions are effective in separating the two genotypes. It should be realized that the ages of the bulls range from 15 months to 13 years with no correction for age effects on any of the characteristics. Age is known definitely to affect both head length and head width, and thus the cephalic index (Kidwell *et al.*, 1952). Had there been corrections for age effects of all the characteristics, perhaps the separation would be more complete. With the accumulation of more data, especially on proven homozygous normal animals, refinements should be possible. It is suspected that there are other diagnostic points on the profile that may be of value in the further separation of the two genotypes.

The statement is often made that the dwarf problem is over-emphasized

and that the research effort now devoted to it is not warranted. The data summarized in tables 7 and 8 were first assembled at the request of, and in cooperation with, the several breeders involved who had a high frequency of the dwarf gene. These represent herds throughout the country that have popular breeding. The tables are identical with the original summaries except

TABLE 7

A SAMPLE OF ALL HERD BULLS STUDIED FROM A FEW HERDS IN WHICH THE FREQUENCY OF THE DWARF GENE IS HIGH. *(Both the profile type and the progeny test are given for each sire, which is identified by code number. These data were originally compiled at the request of and in cooperation with the individual breeders involved.)*

Code No.	Profile type	Proven genotype	Code no.	Profile type	Proven genotype
W 1	Carrier	Heterozygous	12	Dwarf-free	Homozygous
W 2	Carrier	Unproven	W 29	Carrier	Heterozygous
W 3	Carrier	Heterozygous	W 30	Carrier	Heterozygous
W 4	Carrier	Heterozygous	W 31	Dwarf-free	Homozygous
W 5	Type I	Heterozygous	W 32	Carrier	Heterozygous
W 6	Carrier	Heterozygous	W 33	Carrier	Heterozygous
W 7	Carrier	Heterozygous	W 34	Carrier	Heterozygous
W 8	Carrier	Heterozygous	W 35	Carrier	Heterozygous
W 9	Carrier	Heterozygous	W 36	Carrier	Unproven
W 10*	Carrier	Unproven	W 37	Carrier	Heterozygous
W 11	Type I	Homozygous	W 38	Carrier	Heterozygous
W 12	Carrier	Heterozygous	W 39	Carrier	Heterozygous
W 13	Carrier	Heterozygous	W 40	Carrier	Unproven
W 14	Carrier	Heterozygous	W 41	Dwarf-free	Unproven
W 15	Carrier	Heterozygous	W 42†	Dwarf-free	Heterozygous
W 16*	Carrier	Unproven	23	Dwarf-free	Homozygous
W 17*	Carrier	Unproven	W 45	Carrier	Heterozygous
W 18*	Carrier	Unproven	W 46	Carrier	Heterozygous
W 19*	Carrier	Unproven	W 47	Carrier	Heterozygous
W 20*	Carrier	Unproven	W 48	Carrier	Heterozygous
W 21*	Type I	Unproven	W 49	Carrier	Heterozygous
W 22*	Carrier	Unproven	W 50	Carrier	Heterozygous
W 23	Type I	Heterozygous	W 51	Carrier	Heterozygous
W 24	Carrier	Heterozygous	14	Dwarf-free	Homozygous
W 25	Carrier	Heterozygous	W 53	Carrier	Unproven
7	Dwarf-free	Homozygous			

* Herd bull prospect.
† Predictions of genotype did not agree with results of progeny test. This bull has a deep groove along the median suture in the region of MFP.

that they are handled in such a manner that the identity of individual herds and animals cannot be recognized. In all cases the object of the summary was herd analysis and the organization of a breeding program that would permit the selection of dwarf-free bulls and the control of dwarfism. Table 7 shows the extent of proven heterozygous sires being used in some herds. Other herds not included in this summary have as high a percentage of herd sires that are dwarf carriers. Mention should be made of the almost perfect agreement between the profile type and the genotype determined by progeny test. Even though the number of homozygous sires is small, they can be identified consistently.

A much lower percentage of the bulls assembled in table 8 have been

proven by progeny tests. In these herds, the prevailing practice was to send cows that produced dwarf calves to the butcher before the next breeding season; hence there was not an accumulation of proven heterozygous cows. The only selection against dwarfism was the immediate elimination of carrier cows. At the time the original table was compiled, only 15 of the bulls had been proven by progeny tests. Recently two more were proven to be

TABLE 8

SAMPLE OF ALL SIRES FROM A FEW HERDS THAT HAD BEEN DISCARDING HETEROZYGOUS COWS AS SOON AS THEY WERE PROVEN. *(These data were compiled at the request of and in cooperation with the individual breeders involved.)*

Code no.	Profile type	Proven genotype	Code no.	Profile type	Proven genotype
W 54	Carrier	Heterozygous	W 88	Carrier	Unproven
W 55	Carrier	Unproven	W 89	Type I	Unproven
20	Dwarf-free	Proven homozygous	W 90	Carrier	Unproven
21	Dwarf-free	Proven homozygous	W 91	Carrier	Unproven
W 58	Carrier	Unproven	W 92	Carrier	Unproven
W 59	Carrier	Unproven	W 93	Carrier	Unproven
W 60	Carrier	Unproven	W 94	Carrier	Unproven
W 61	Carrier	Unproven	W 95	Carrier	Unproven
W 62	Carrier	Unproven	W 96	Carrier	Unproven
W 63	Carrier	Unproven	W 97	Carrier	Unproven
W 64	Carrier	Unproven	W 98	Carrier	Unproven
W 65	Carrier	Unproven	W 99	Carrier	Unproven
W 66	Carrier	Heterozygous	W 100	Carrier	Unproven
W 67	Carrier	Heterozygous	W 101	Carrier	Unproven
W 68	Carrier	Unproven	W 102	Carrier	Unproven
W 69	Carrier	Unproven	W 103	Carrier	Unproven
W 70	Carrier	Unproven	W 104	Carrier	Unproven
W 71	Carrier	Unproven	W 105	Carrier	Heterozygous
W 72	Carrier	Heterozygous	W 106	Carrier	Unproven
W 73	Carrier	Heterozygous	W 108	Carrier	Unproven
W 74	Carrier	Unproven	W 109	Carrier	Heterozygous
W 75	Carrier	Unproven	W 110	Dwarf-free	Unproven
W 76	Carrier	Unproven	W 111	Carrier	Unproven
W 78	Carrier	Unproven	W 112	Carrier	Unproven
W 79	Carrier	Unproven	W 113	Carrier	Heterozygous
W 80	Carrier	Unproven	22	Dwarf-free	Proven homozygous
W 81	Carrier	Unproven	W 115	Carrier	Heterozygous
W 82	Carrier	Unproven	W 116	Carrier	Unproven
W 83	Carrier	Unproven	W 117	Carrier	Heterozygous
W 84	Carrier	Unproven	W 118	Carrier	Heterozygous
W 85	Dwarf-free	Unproven	W 119	Carrier	Unproven
W 86	Dwarf-free	Unproven	W 120	Carrier	Heterozygous
W 87	Dwarf-free	Unproven	W 121	Carrier	Unproven
W 87A	Not determined	Unproven			

dwarf carriers. The identity of the two newly proven bulls was given by name, and since the original identifications were by tattoo number, the exact identities of the last two heterozygotes have not been ascertained. A total of 14 bulls are proven heterozygous, and three—numbers 20, 21, and 22, shown in table 5—are proven homozygous normal.

The bulls shown in table 8 are of still more significance. They are a part of the first extensive field test to see if a field worker can collect profiles and essential data and send them to a central laboratory for determining whether or not dwarf-carrier and dwarf-free bulls can be identified from head profiles.

These data were collected by Roubicek and Hilston. The owners withheld all information on each individual except the tattoo number. The data were sent to the California laboratory for classification and the predictions of genotype. These predictions were sent to the owner and compared with the individual progeny test from the records of the owner. There was complete agreement between the two. The data from tables 7 and 8 show three things: (1) the wide prevalence of the dwarf gene; (2) the close correlation between type of head profile and proven genotype; and (3) that it is possible to predict genotype from the head profile.

TABLE 9

SUMMARY OF FIELD TESTS WITH BULLS TO DETERMINE IF THE PROFILE CAN BE OBTAINED IN THE FIELD BY DIFFERENT OPERATORS AND THE GENOTYPE DETERMINED IN A CENTRAL LABORATORY

Test	Prediction of genotype from the profiles		Results of progeny tests		Errors	Alleged homozygous but data on progeny tests either were not submitted or proved inadequate
	Carrier	Dwarf-free	Carrier	Dwarf-free		Undetermined
1	20	2	21	1	1	0
2	25	1	26	0	1	2
3	7	0	7	0	0	0
4	43	0	43	0	0	0
5	25	0	25	0	0	1
6	31	6	32	5	1	0
7	11	1	12	0	1	0
8	59	16	60	15	1	1
Totals	221	26	226	21	5	4

After the field trial described above was completed, extensive field tests involving several operators were organized. In order to assure proper standardization most of the operators participating received considerable personal instruction in taking profiles and head measurements; some, however, received written instructions only. These tests covered states from Maine to California and from the Canadian border to the Mexican border. Altogether 16 different operators participated in collecting the profiles. All the profiles were processed in a central laboratory either at the University of California or the Bureau of Animal Industry laboratory at Denver. The profiles were evaluated by Gregory or by a laboratory technician. All of the profiles that were processed are included in this summary. None of the profiles used for determining the diagnostic points and for developing means of differentiating the dwarf-free and dwarf-carrier genotypes are included in the summary of table 9.

It was requested that two median profiles and one off (O^1 X) profile (fig. 1) be taken of each animal. If the two median profiles did not agree reasonably well, obviously one or both were faulty and the animal was to be reprofiled before an estimate of genotype should be attempted. Most of the operators

did not use the field card, which when filled in indicates the nature of the MFP and the nature of the frontal suture in the diagnostic area.

There was no uniform method of identifying the bulls in the different tests. Several operators used code numbers, while others used the tattoo or horn number. In neither case was the breeding of the animal revealed. Other operators gave the name of the animal, either official or unofficial, and a few gave both official name and registration number. The earlier predictions of genotype were made under the more primitive method first developed for differentiating between the two genotypes. Later in the study when discriminant functions were developed, they replaced the original method. It should be realized, however, that most of the predictions were made on the basis of the more primitive method.

The practice followed in making predictions was to list each animal and give its profile classification or one or more discriminant functions. The significance of the classification with respect to genotype was made clear. Two copies were sent to the operator who was to supply the results of any progeny tests. One copy was to be returned to the central laboratory, the other retained by the operator. Most of the animals were unproven at the time they were profiled. As they were proven the operator was to notify the central laboratory of the results of each test. Thus, the representative at the central laboratory had made a definite commitment in writing and the field operator had a copy. These data constitute the "official record" summarized in table 9. This is broken down for convenience into eight different tests in which 16 different operators contributed data. Unproven bulls are not considered in this analysis except under special circumstances (table 9, column 7). These will be discussed briefly in connection with progeny tests.

The bulls included in tests 1 to 7, inclusive, were handled by 15 different operators representing a wide area of the United States. The operators in tests 1, 6, and 7 had considerable experience in taking profiles and collecting the field data. The data for tests 2, 3, and 4 were each collected by a single operator, who had been given a fair amount of training before attempting the field work. The data included in test 5 were collected by 11 different operators. Some of these operators had no training other than written instructions; others had a few minutes or a few hours of instruction. All the data in test 8 were collected by Gregory, and most had been obtained before the other tests were undertaken.

Table 9 demonstrates that it is possible consistently to identify dwarf-free and dwarf-carrier bulls, but a small percentage of heterozygotes is also classified as dwarf-free. The evidence indicates that there is a greater tendency to classify heterozygous bulls dwarf-free than to classify dwarf-free bulls heterozygous. Since a discriminant function is the logical basis for predicting genotype and an overlapping zone must be recognized, this is now taken into account in the evaluation. Ordinarily the four animals listed in column 7 would be classified as unproven, but they are recognized here because either the operator or owner involved insists that they are "clean." No animal is considered homozygous normal in this test unless there is sufficient data to establish the exact probability of the level of homozygosity. This condition has not been met in any of these cases. The bull in test

8 (column 7) offers an interesting example. His profile was definitely of the carrier type, yet the owner insisted that he had never sired a dwarf when bred to many carrier cows. When breeding records, complete with abortions, stillbirths, and early deaths, were demanded to substantiate the claim, no such records were available nor had such data ever been recorded. Even though a breeder may be entirely honest, as this one was, his memory is not to be trusted for reliable progeny tests. If there is sufficient need, the results of these several different field tests will be presented in detail later (Gregory *et al.*, unpublished).

After all the tests reported above were completed, Gregory profiled all the herd bulls of a few ranches that had registered herds of similar popular breeding. Within the last two years these herds had produced a few dwarf calves. When the data were collected and analyzed, knowledge of the genotypes of all the proven animals was withheld from the investigators until the discriminant functions were calculated. The data on the bulls were handled in the usual manner, and the four different discriminant functions discussed earlier (figs. 23, 24, 25, and 26) for animals of known genotypes were applied to this new population of unknown genotypes. Even though the discriminant functions used in figures 23 and 24 are to be replaced by the one in figure 25, it seemed desirable to use all the discriminant functions in these comparisons.

The distribution of these bulls is somewhat unique because a much higher percentage falls within the range characteristic of the proven homozygous normal animals. Since good records were kept in all these herds and the owners were cooperative, arrangements were made to check the records to determine if an appreciable number of the bulls profiled were proven from the fortuitous matings that had been employed. The primary interest was in the bulls that the profile indicated were homozygous. The only feasible way to check for progeny tests was to use daughters of proven heterozygous bulls as tester cows. A test was also made to explore the possibility of using as tester animals daughters of unproven bulls that profiled as carriers. All the data thus far presented indicate that this should be a rather reliable test. Where these progeny tests were made, all abortions, stillbirths, and deaths before one month of age were taken into account. Calves that are stillborn or die before one month of age that are not classified as dwarfs are considered unclassified. This is justified, since many dwarf calves that die early may not be recognized as dwarfs and thus pass as normal calves. The details of these progeny tests are summarized in table 10. Five of these bulls can be assumed to be homozygous at probability levels of from higher than 1 to 8 per cent on the basis of standard progeny tests. If the validity of the progeny test used is accepted, three of the bulls may be assumed to be homozygous on a probability level of 1 per cent. Bull 534 is proven homozygous at the 3 per cent level if the two methods of testing are combined.

Attention is now directed to other bulls in this test that profile as heterozygotes; certain other pertinent information indicates that they may be heterozygous, yet not one has sired a dwarf calf with proven certainty. The pedigree network (fig. 31) of bull I strongly indicates that he carries the dwarf gene. Furthermore, he falls in the carrier distribution of figures 27, 28, 29, and 30. He sired a "deformed" calf that was killed by coyotes at 2 days of age. Since

no one now remembers this calf, it can not be classed as a dwarf with certainty. Bull V, a son of I, profiles as a heterozygote and has sired two carrier cows (fig. 31). Another bull profiled as a heterozygote sired an "abnormal" calf from a mating that should be expected to produce dwarfs. Here again there is no certainty that this abnormal calf was a dwarf. In addition to the

TABLE 10

STATUS OF THE PROGENY TESTS OF 9 BULLS ASSUMED TO BE FREE FROM THE DWARF GENE ON THE BASIS OF THE HEAD PROFILES. *(These bulls are from the special test to check the validity of the hypothesis that dwarf-carrier and dwarf-free bulls can be differentiated from the head profile. See figures 27, 28, 29 and 30 and the text.)*

Bull	Type of progeny test		
	1 Probability of homozygosity based upon standard progeny tests using daughters of proven heterozygous sires as tester cows	2 Probability of homozygosity based upon the profile of the sire of the test cows. Here sires that had a profile which indicated heterozygosity were assumed heterozygous	1 and 2 combined
526		Greater than 1% Total progeny 50	
527		Greater than 1% Total progeny 63	
528	At 7% level		Greater than 1%
529	At 5% level		
530		Greater than 1% level Total progeny 33	
531	At 8% level		Greater than 1% level
532	At 4% level		Greater than 1%
533	Greater than 1%	At 10% level	
534	14 test progeny—all normal	13 test progeny—all normal and one stillborn	At 3% level

bulls specifically mentioned, 11 other bulls sired by Bull I profile as heterozygotes. Furthermore, all the data indicate that Bull I is a potent factor in the high frequency of the dwarf gene in the population.

When all the data are considered in this test, they strongly support the conclusion that the head profile offers a reliable means for differentiating between dwarf-free and dwarf-carrier genotypes. The distributions of this population for the discriminant functions are shown in figures 27, 28, 29, and 30. Compare the distributions of figures 27 with 23, 28 with 24, 29 with 25, and 30 with 26, and note the similarity of distributions for the population of proven genotypes with the population of proven or partially proven genotypes for each discriminant function. Four bulls that sired dwarfs plotted as

indicated on figures 27, 28, 29, and 30. The positions of unproven but suspected heterozygous bulls are indicated. One of these bulls (I, fig. 31) never sired a dwarf but was a suspected heterozygote because all the proven heterozygotes of both sexes, except one, were descended from him.

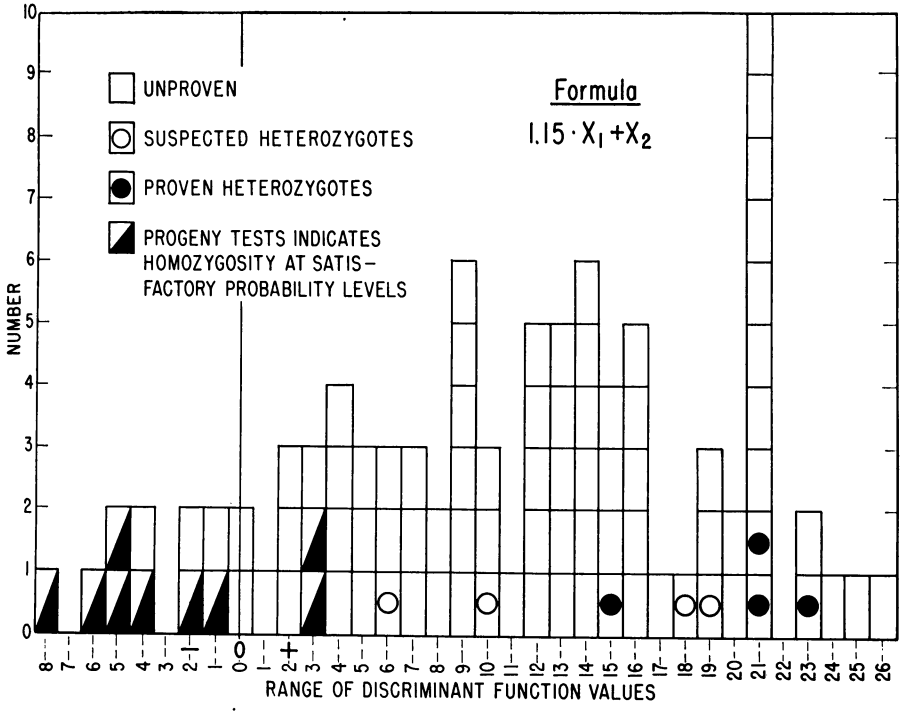


Fig. 27. The discriminant function $1.15X_1 + X_2$ applied to a group of herd bulls whose genotype was unknown until after the discriminant functions were calculated. The four bulls proven to be heterozygous, the suspected heterozygotes, and the nine proven by progeny tests to be free from the dwarf gene are indicated.

DISCUSSION

It should be remembered that neither the key nor any of the discriminant functions is applicable to Type I heads. Predictions should not be attempted unless there are two medium profiles between which there is good agreement. This is comparable to duplicate determinations in routine chemical analyses. Occasionally asymmetrical heads are encountered. The genetic status of animals with such heads has not been established. It is certain that in the population studied the dwarf-carrier and dwarf-free genotypes can be effectively differentiated. The accuracy and effectiveness of the profile method in the control of dwarfism is contingent upon whether or not the sample studied is truly representative of the national population. The sample drawn from the western states is believed to be quite typical of that area. Many of these herds have furnished foundation and replacement stock for not only the western states but all the other regions. The herds have been sampled by working

directly with the breeder or indirectly, subject to sales and dispersions of breeding stock to other herds. It is assumed that the herds in the Rocky Mountains and Plains areas have had a more profound effect upon the breed, as a whole, than those of any other region. Small samples were obtained from the Corn Belt states and the southern region. The prediction of genotype was equally effective for all regions and states.

In order to test the possibility that differences in breeding might account in whole or in part for the differentiation manifest in figures 23, 24, 25, and

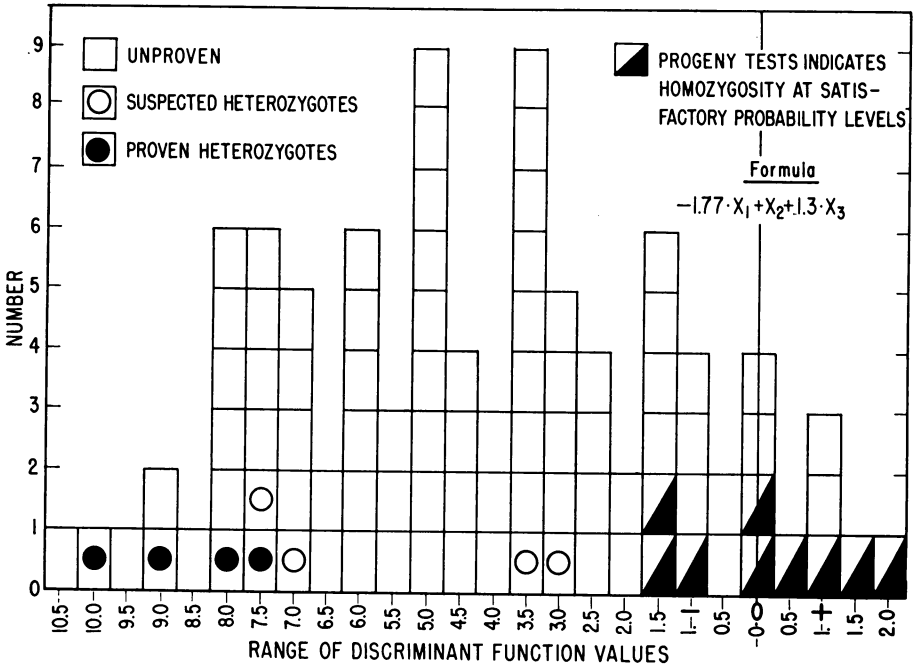


Fig. 28. The discriminant function $-1.77X_1 + X_2 + 1.3X_3$ applied to the same group of bulls shown in figures 27, 29, and 30. The four bulls proven to be heterozygous, the suspected heterozygotes, and the nine proven by progeny tests to be free from the dwarf gene are indicated.

26, a discriminant function was calculated from two herds of different breeding that supplied an appreciable number of homozygous and heterozygous bulls proven by progeny tests at acceptable probability levels. The computed function $6.0X_1 - 9.67X_2 + X_3$ does not differentiate the two herds.[8] The frequency distributions for these two herds are shown in figure 32. The fact that the herds do not differentiate by this function indicates that the differential patterns of the distributions shown in figures 23, 24, 25, and 26 are not caused by pedigree differences.

If any herds do not conform to this general scheme, they are probably closed herds, which practice inbreeding and are not using breeding stock

[8] This formula can be simplified further. However, this does not seem necessary since it will not be generally used.

of the popular blood lines. A herd meeting the above specifications was found, and for some time it was thought that it might be exceptional. A check of parentage determination by means of blood types revealed that one exceptional animal could not have been the offspring of his alleged sire (C. P. Stroble, 1953).[9] This herd is being further investigated.

Consideration should be given to the specificity of the mid-forehead prominence associated with the dwarf gene. Is it gene-specific and conditioned solely by the gene in question, or can several independent genes cause the

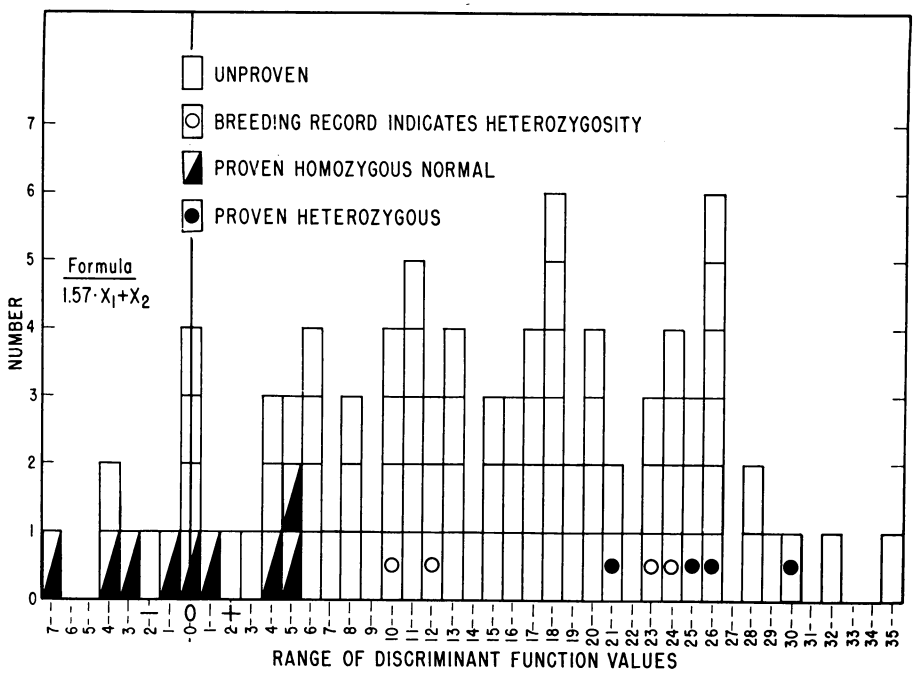


Fig. 29. The discriminant function $1.57X_1 + X_2$ applied to the same group of bulls shown in figures 27, 28, and 30. This discriminant function is to replace the ones used in figures 23 and 27, and 24 and 28 respectively. Proven or suspected heterozygotes and the nine bulls proven by progeny tests to be free from the dwarf gene are indicated. Note the similarity of distribution with the bulls of proven genotypes shown in figure 25.

expression? All the comprest animals profiled had a marked manifestation of the mid-forehead prominence on the median profile. This type of dwarf heterozygote has been discussed earlier, and it should be remembered that the expressions in both the heterozygous and homozygous forms are more drastic than the corresponding genotypes of the type of dwarfism with which this paper is primarily concerned. It was mentioned earlier that several morphologically different types of dwarfs have been observed. Although breeding tests are lacking in most cases, the physical differences between some of these dwarfs make it improbable that they are conditioned by a common gene; yet all manifest a mid-forehead prominence. Lethal dominant achon-

[9] Personal communication.

droplastic calves of the Dexter type certainly manifest this bulging forehead (Seligmann, 1904; Crew, 1924). On the basis of this evidence, the logical conclusion is that the mid-forehead prominence may be caused by any of several different genes conditioning dwarfism. It should be emphasized that all of these dwarfs in question are of a cretin type. Thus the mid-forehead prominence is assumed to be associated with several different forms of cretinism. When such cretin-conditioning genes have expression in the heterozygous state, a certain amount of confusion may be encountered in progeny

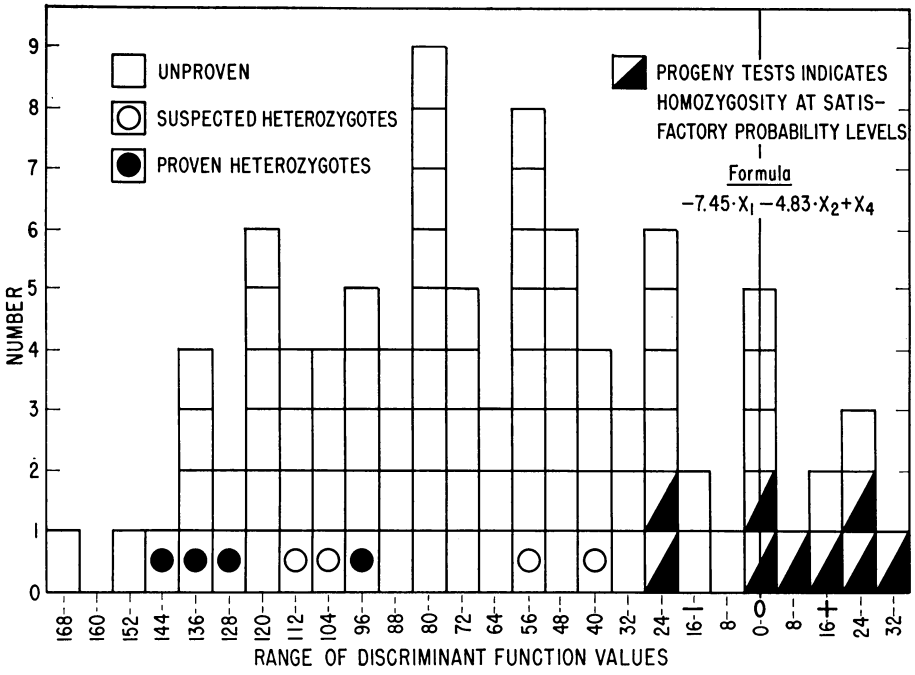


Fig. 30. The discriminant function $-7.45X_1 - 4.83X_2 + X_4$ applied to the same bulls shown in figures 27, 28, and 29. The four bulls proven to be heterozygous, the suspected heterozygotes, and the nine proven by progeny tests to be free from the dwarf gene are indicated.

tests until the inheritance and relationships of all the genes involved are clearly understood. The experimental anatomists who have devoted attention to skull shape are well aware of the influence of the thyroid gland in determining head and body form (Liddell, 1925; Dye and Maughan, 1929; Dye and Kinder, 1934; and Todd and Wharton, 1934). The experiments of Spielman *et al.* (1945) show that the response of the bovine to thyroidectomy is in line with that of other animals. Furthermore, on the basis of the expression of the dwarf gene in the heterozygote, it seems that the frontal bones are more sensitive and respond more readily than the other parts of the body that are subject to the cretin modification. This is in agreement with the observations of the creeper gene in fowl, which exerts a general effect upon development but elicits differential responses in different parts of the body

(Landauer, 1940). A tenable conclusion is that there are several genes in cattle in either the heterozygous or homozygous state that provoke, in part at least, the modifications constituting the cretin expression, and that the heterozygote displays a milder expression than that of the homozygote. Cretin-conditioning genes that have expression in the heterozygous state are well known and have been reported in several species. The classical example is

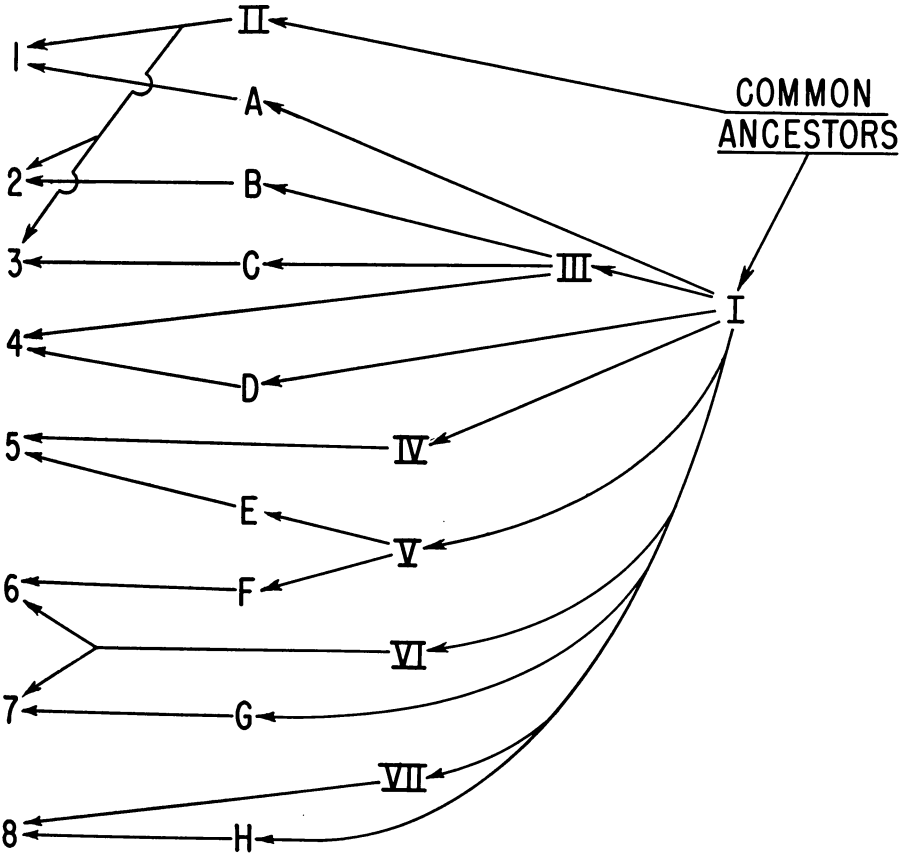


Fig. 31. A pedigree network of eight dwarf calves numbered one to eight from the herds shown in figures 27, 28, 29, and 30. Cows are indicated by letters and bulls by roman numerals. Bulls I through VII manifest distinct carrier profiles on figures 27, 28, 29, and 30. Bulls I and V have never sired dwarfs, but this figure indicates that they are probably heterozygous. All the other bulls shown here are proven heterozygotes.

that of the bulldog condition in cattle in which the heterozygote is intermediate (Crew, 1924; the heterozygous comprest condition discussed earlier in this report is another (Stonaker, 1953).[10] Genes with action somewhat similar to these have been studied in the rabbit. Thus, in one type of hereditary achondroplasia, it was possible to differentiate between heterozygous and homozygous normal from the head shape, which primarily involved an

[10] Personal communication.

effect upon the form of the frontal bones (Green, 1940); in another, dwarfing gene heterozygotes not only had a different ossification pattern, but they could be differentiated from homozygous normals by a shorter ear length that became apparent after seven or eight weeks of age (Crary and Sawin, 1949). The creeper gene of the fowl, mentioned earlier, also has many forms of heterozygous expression, as demonstrated by the meticulous studies of Landauer (1940).

Thus far, only dwarf genes with expression in both the heterozygous and homozygous states have been considered. A gene could conceivably exist that

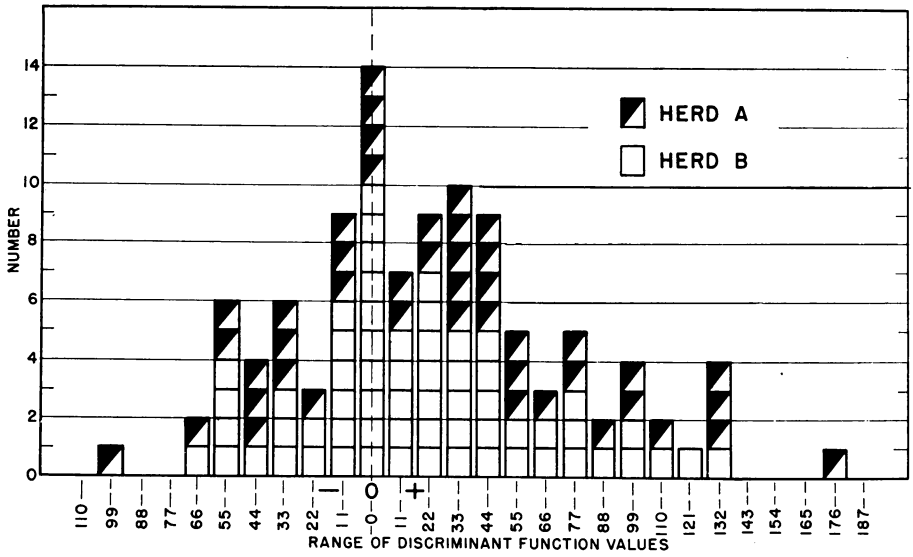


Fig. 32. A histogram showing the distributions of two large unrelated herds when the discriminant function $6.0X_1 - 9.67X_2 + X_{33}$, computed from them is applied. Each of these two herds supplied an appreciable number of animals of proven homozygous and heterozygous genotypes used in the study.

conditions only the more susceptible modifications of the cretin syndrome, such as a bulging forehead, without being associated with dwarfism. This could be a fixable recessive gene (not lethal), or it could be caused by a specific gene interaction, depending upon epistasis. The genetic basis for the mid-forehead prominence conditioned by each specific gene should be investigated, as well as all the various environmental factors influencing the expression of these specific genes. Both genetic and environmental effects should be integrated with anatomy and, if possible, with embryology.

The population sampled was large, and the proven sires were consistently differentiated by the relationship of the diagnostic points on the profile; therefore it is unlikely that a high percentage of exceptional animals exists. Admittedly the number of proven homozygous animals is limited, but when the data as a whole are considered, the probability of a high percentage of aberrant animals in the population seems remote. Early in the study and throughout its course many herds were sampled because the owners were

confident that they were dwarf-free, but many bulls alleged to be dwarf-free possessed carrier-type profiles. To date all that have been progeny-tested have proven to be heterozygous for the dwarf gene.

Predictions of genotype based upon the original key have also been made on several hundred unproven bulls. It is unlikely that the results of all those proven by progeny tests will be reported. The errors on these predictions should be between 2 and 4 per cent. Now that discriminant functions are available, it will not be necessary to make predictions as such. The different discriminant functions can be calculated for a bull of unknown genotype and then compared with the distributions of bulls of each established genotype. Thus the genotype of an undetermined animal can be established or expressed in terms of probability.

The results of these progeny tests make the authors believe it is highly improbable that a high percentage of mature bulls possessing a distinct dwarf-carrier type profile and descended from popular breeding or from known heterozygotes would prove other than heterozygous. Certainly more progeny tests are needed. Breeders who desire to develop dwarf-free herds should see that their sires are profiled and progeny-tested whenever possible and at an early age. The results of the progeny tests and all pertinent data should be placed at centers compiling such data. Animals with unusual or exceptional profiles should also be progeny-tested, and in some cases paternity should be checked by blood typing. This is the only way in which the complete possibilities and limitations of this or any other method of detecting the two genotypes can be evaluated. Since a closed herd not related to animals of popular breeding may have animals that are exceptional, pedigree should also be taken into account in predicting genotype for dwarfism from the head profile. This has not been done to date on any bulls classified for genotype.

The effective genetic control of dwarfism is dependent upon the recognition at an early age of the dwarf-carrier and dwarf-free genotypes. It is already possible to differentiate some successfully as early as 15 months of age by means of the profilometer. Profiles on several hundred bulls from 6 to 20 months of age have been accumulated from herds that furnish favorable genetic material. A large number of these now have mature profiles, and the genotypes of a substantial number have been or are being determined. The status of the determination of genotypes at early ages should become rather well advanced within the next few months. Since cows are less favorable genetic material than bulls, studies on sires were pursued with more vigor. There is expression of the dwarf gene in the median profile of the cow, and considerable data have been amassed. These are now being analyzed.

It was mentioned earlier that the dwarf gene enhances most of the characteristics that the cattle judge and breeder looks for in a desirable herd sire (Ware, 1952). It has been observed in many herds that once a breeder introduces a dwarf-carrier bull into a cow herd free from the dwarf gene he unconsciously but consistently favors heterozygous sires in further selections until a preponderance of the herd sires are heterozygous. The evidence observed in the field indicates that a disproportionately large number of

the homozygous normal bulls are castrated or go into commercial herds, and the heterozygous bulls are preferred by breeders and commercial cattlemen who try to be more discriminating in the selection of sires. Thus in recent years the frequency of the dwarf gene has increased rapidly in registered and most commercial herds. Until the trend to castrate homozygous dwarf-free bulls or send them to commercial herds is reversed, there will continue to be too few homozygous normal bulls to meet the needs of registered breeders and commercial cattlemen. Perhaps the major basis for the selection of heterozygotes is earliness of maturity. Even though the dwarf gene does enhance some of the characteristics that breeders look for in sires, this does not exclude the possibility of obtaining desirable animals free from the dwarf gene. Breeders of registered cattle should exert themselves to select dwarf-free herd sires.

Since a higher percentage of young bulls now available are dwarf carriers than were the bulls available five or six years ago, breeders might consider recalling, for service in registered herds, older bulls now being used in commercial herds that profile dwarf-free. This would be a certain way to reduce the frequency of the dwarf gene immediately and increase the number of homozygous normal young bulls in the succeeding calf crop. Commercial herds that have never suffered any loss from dwarfism can use dwarf-carrier bulls for three or four years and at the same time select replacement heifers with little or perhaps no loss from dwarfs. Any commercial breeder who does this, however, should follow heterozygous sires with dwarf-free bulls. On the other hand, commercial breeders now suffering a loss from dwarfs can ill afford to continue using heterozygous sires.

Since the application of this technique for differentiating mature dwarf-free and dwarf-carrier bulls is now ready for field application, consideration has been given to implementing a program that would permit breeders to use this method of identifying the two genotypes in the selection of sires. Profiles must be taken with a standardized instrument by trained personnel before any interpretation should be attempted. The difficulty of excluding personal bias together with the reluctance of a buyer to accept results obtained by a rancher on his own animals precludes the possibility of ranchers' doing their own work.

Since the frequency of the gene is high in the breeding cows of many herds, and heterozygous bulls are definitely favored over homozygous normals, the percentage of heterozygous progeny available for breeding replacements (after dwarfs have been removed) in many herds may exceed 50 per cent. The percentage of heterozygotes may be further augmented by the heavier culling of homozygous normal sibs. Thus the percentage of heterozygous young bulls offered as breeding stock can run fantastically high at sale time. Data on young bulls from several herds indicate that this may be the actual situation. If this proves true, breeders may find it difficult to classify their own animals without bias or with the aloofness necessary for successful selection against the heterozygote. Properly trained personnel should have no difficulty in taking true profiles. If these could be sent to a central laboratory, far away from pressures, to be classified by trained technicians, the practice should actually prove more satisfactory for the individual

breeder and the industry as a whole. The authors strongly recommend federal or state agencies with trained, responsible persons to interpret profiles for breeders. Purchasers of herd sires may find it necessary to safeguard their investment by insisting that bulls bought on the basis of a head profile be profiled with standard equipment and that the interpretation be made by trained personnel under the supervision of an unbiased state agency.

There is widespread belief that in general heterozygotes are superior to homozygous normals. Cattlemen and animal husbandmen seem to be confused, failing to differentiate between what may be a fancier's viewpoint on the one hand and efficiency of the animal to utilize food for beef production on the other. Heterozygotes cannot be superior to homozygous normals unless they more efficiently convert food into edible beef of similar or superior quality. If heterozygotes do prove superior, there is always the possibility of loss from dwarfs. It would be necessary for the heterozygote to show a marked superiority in both food utilization and carcass quality before the commercial breeder could afford to consider use of the dwarf gene in beef production. If the principal role of the dwarf gene rests solely on fancy points, the existence of a high frequency of the dwarf gene in the population cannot be justified. On the other hand, if the dwarf gene is of real economic worth in commercial production, means should be developed to use it without loss from dwarf segregates.

SUMMARY

1. A survey of registered and commercial Hereford herds throughout the United States reveals that the incidence of dwarfism is high and is increasing. The dwarfism is conditioned by an autosomal recessive gene with complete penetrance. Breeders for many years have definitely, though unconsciously, favored the heterozygote in the selection of sires, thus building up a high frequency of the gene in both registered and commercial herds. Since it was evident that breeders could recognize the heterozygotes with almost unfailing accuracy in sires, this investigation was undertaken specifically in an attempt to differentiate between heterozygous and homozygous normal genotypes by means of physical measurements. The genetic relationship of this dwarf-conditioning gene to other genes that produce somewhat similar phenotypic effects is discussed.

2. The median head profile was studied in detail from approximately 500 horned Hereford bulls, mostly of popular breeding. Of these over 325 were of determined genotype with respect to the dwarf gene. Most of the sample came from the western states, although some were obtained from the north-central, eastern, and southern regions. The age range was from 15 months to 13 years. From this number, more than 250 were proven by progeny test to be heterozygous for the dwarf gene, while more than 30 were proven by progeny test to be free from the dwarf gene. An additional number used as checks were either from dwarf-free herds, or were partially proven to be dwarf-free but proven below the 10 per cent level; they were assumed to be homozygous normal.

3. The head profile of the living animal was related to specific skull structures, and it was possible to locate on the profile the approximate juncture

of the nasal bones with the frontals (NFJ), the approximate juncture of the parietal bone with the frontals (PFJ), and the approximate point on the frontals where the dwarf gene caused the maximum prominence or bulge (MFP). Profile types were classified by the relations of these three points. In herd bulls Class I profiles were found in only 5 per cent of the sires. Profile types of Classes II and III made up the remaining 95 per cent of the population. These proportions may be different in unselected populations.

4. The dwarf gene in the heterozygous state has such a marked effect upon the frontal bones in bulls that heterozygous and homozygous normals can be differentiated, with a high degree of accuracy, from the relationships of the three diagnostic points on the head profile. It is possible to differentiate the two genotypes by several different methods. All the diagnostic techniques demonstrated are highly efficient. The discriminant function using the formula $1.57X_1 + X_2$ should replace the first two given in figures 23 and 24. The formula $-7.45X_1 - 4.83X_2 + X_4$ may be used effectively in differentiating the two genotypes. While none of the animals in this report are less than 15 months of age, other data clearly indicate that dwarf-free and dwarf-carrier genotypes can be identified in bulls at an earlier age. Approximately 2 to 3 per cent of bulls possessing profiles of Classes II and III have a bilobed midforehead prominence. The median profile will not differentiate between the two genotypes in bilobed animals; however, the bilobed MFP may be diagnosed by palpation. Since the Class I profile is rare in herd sires, as yet no attempt has been made to subdivide that class into heterozygous and homozygous genotypes; however, the assumption is that this can be done when profiles of enough proven animals of both genotypes are available. Even though there is expression of the dwarf gene in the heterozygous state in females, they are not considered in this study.

5. Several tests in the field under varying conditions indicate that it is feasible to use this method of diagnosis for differentiating between dwarf-carrier and dwarf-free bulls for breeders and commercial cattlemen. The organization of such a program and the problems to be overcome are discussed.

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