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AN EVALUATION OF THE ACCURACY OF THE JOHNSTON GRID IN CEPHALOMETRIC GROWTH PREDICTION

by

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AN EVALUATION OF THE ACCURACY OF THE JOHNSTON GRID
IN CEPHALOMETRIC GROWTH PREDICTION

Abstract

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Although cephalometric growth prediction is highly controversial within the orthodontic specialty, a computerized commercial prediction service has been made available by Rocky Mountain Data Systems, Inc. Recently, an additional method--the so-called Johnston Forecast Grid--has been developed. Although it is claimed that the grid produces forecasts of accuracy comparable to that of more complex methods, published validations are fragmentary and somewhat contradictory.

Accordingly, an independent validation of the grid method was undertaken on a sample of 100 subjects for intervals ranging from two to ten years. In addition, its accuracy was compared to an additional sample of 20 five-year forecasts generated by the commercial service.

Average errors, average absolute errors, and root mean squared errors were calculated for both the grid and computerized forecasts.

The following conclusions were drawn:

1. The accuracy of grid forecasts decreased in direct proportion to the prediction-interval.
2. The accuracy of the grid forecasts were almost identical to that of predictions generated commercially.

3. Estimates of accuracy reported here are, in certain respects, different from those published for smaller samples.

4. Reduction in technical error would be necessary to effect a marked improvement in the accuracy of short-term forecasts.

5. Improved accuracy for long-range forecasts will require a genuine breakthrough in our understanding of the mechanisms of craniofacial growth.

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DEDICATED

TO

My parents, with everlasting love, honor, and respect;

And, for posterity, to my niece, Diane Marie and my nephew, James Edward.

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INTRODUCTION

Since its introduction over four decades ago, the cephalometric technique has gained almost universal acceptance among orthodontic specialists. At present, the use of cephalometrics as an aid in description, classification, analysis, and monitoring of treatment seems to be well-established, valid, and, in a general sense, uncontroversial. However, its most recent application, growth prediction, is still highly controversial.

Despite the absence of a concensus regarding the validity and usefulness of cephalometric growth prediction, one approach--the Ricketts "arcial" method--has nonetheless gained a certain degree of popularity. Recently, the Ricketts technique has been modified and, by utilizing a computer to execute the complex geometry, has been offered as part of a commercial cephalometric service.

However, in view of the considerable cost and the somewhat limited prediction efficiency seen in a recent validation, it is perhaps inevitable that a simpler, less costly method should appear. The recently-introduced Johnston Forecast Grid claims to meet these criteria and, by inference, to be of comparable accuracy.

Accordingly, it is the primary purpose of this investigation to validate the accuracy of this newest scheme in a large series of individual predictions and, secondarily, to compare its accuracy with that of the commercial version of the Ricketts arcial long-range forecast.

REVIEW OF THE LITERATURE

The obvious utility of a method which would permit the orthodontist to forecast accurately the effect of future growth, or of both growth and treatment, no doubt accounts in large measure for the interest in cephalometric prediction that has existed over the last two decades. A review of the relevant literature should provide an appreciation for the evolution of contemporary techniques and serve to define clearly the nature of the problem.

The cephalometric era began with the introduction by Broadbent in 1931 of a precise roentgenographic technique. Several years later, when Broadbent (1937) published data obtained from early Bolton Growth Study records, the groundwork for what came to be known as the "pattern concept" was prepared. This concept, which holds that facial form remains constant during childhood and adolescence, owes much to Broadbent's (1937) diagrams (Figs. 9 and 14, pp. 193 and 198) and his statement that there is an ". . . orderly downward and forward path that is found in the developmental growth pattern of the face of the normal child." It should be noted, however, that the pattern concept, per se, is due to Brodie, not Broadbent.

Brodie (1941), in a now-classic investigation based on longitudinal data derived from a sample of twenty-one males, concluded that facial growth between three months and eight years of age is proportional. The age-span was subsequently (1946) revised to

include a time "prior to birth." In 1946, Brodie reiterated his belief in the proportional growth of bone and soft tissue, and emphasized that any existing disharmonies remain unaltered by growth and "cannot be changed by treatment." In 1953 Brodie noted a few individual changes in pattern between ages eight and seventeen (the most notable of which was the consistent forward movement of the chin point), but he generally adhered to his concept as originally stated. Clearly, at that time, the concept of cephalometric prediction would have been gratuitous, inasmuch as individual craniofacial form was viewed as stable and unalterable throughout the growth period.

Modification of this prevailing concept of growth commenced with the appearance of Björk's (1947) massive cross-sectional cephalometric investigation of adolescent growth-changes of 322 males at twelve years of age and 281 males at twenty years of age. He concluded that ". . . the degree of prognathism of both jaws increases somewhat during the growth period, that of the lower jaw more than the upper jaw, thus straightening the facial profile." In a subsequent (1951) longitudinal study of 150 males from twelve to twenty years, Björk confirmed his previous findings. More recently, Björk's unique metallic implant studies on human samples of five (1955) and 110 subjects (1963) have permitted even more detailed description of the often dramatic changes in the individual growth pattern.

Following Björk's lead, numerous investigators have examined the pattern of facial growth and have generally supported his findings. For example, on the basis of data gleaned from thirty-four cephalometric

series covering a mean age-span of 4.4 to 17.1 years, Lande (1952) concluded that the convexity of the face nearly always decreases due to an increase in mandibular prognathism occurring after seven years of age. Moreover, he ". . . found no correlation between the original facial type at seven years of age and the growth changes at gnathion from seven to seventeen years of age."

Coben (1955), in a longitudinal study of 47 individuals, demonstrated that, on the average, the proportion of facial height to facial depth increased with age during the growth years. Yet, he was more impressed ". . . with the infinite variations in size, form, and growth of all structures" and concluded, somewhat prophetically, that "no characteristic, or combination of characteristics, yields an infallible formula to the growth potential of the individual face."

In a vast, cross-sectional study of the soft tissue profile based on 6,829 subjects, Pelton and Elsasser (1955) arrived at some conclusions which differed from those of Björk and Lande (who both studied the boney profile), but in general concurred that the ". . . basic facial pattern does change between the ages of 6 and 24." Longitudinal studies by Nanda (1955), Meredith et al. (1958), Subtleny (1959), Merow (1962), and Wisth (1972) also showed changes in the pattern of craniofacial growth.

Not only did these studies cause the orthodontic community to re-evaluate Brodie's concept of proportional growth, but also additional investigations demonstrated quite plainly that treatment could alter the face and change its pattern of growth . Ricketts

(1955, 1960a, 1971), Holdaway (1956), and Graber et al. (1968), among others have reported orthodontic--and orthopedic--skeletal changes. Their research seems to indicate that the maxilla may change rather significantly when influenced by heavy Class II elastics, cervical traction, and the vigorous retraction of maxillary incisors combined with lingual root torque. Specifically, they found posterior relocation of anterior nasal spine and, to an even greater extent, point A. According to Ricketts (1960a), "We can no longer accept the maxilla as an immutable structure."

It seems, therefore, that if current concepts embrace the possibilities of change in the individual's craniofacial pattern due to the influences of both growth and treatment, then the search for a technique of cephalometric forecasting is both valid and reasonable.

The various prediction schemes which have been proposed may be grouped according to their underlying mathematical model according to the classification of Hirschfeld and Moyers (1971), which for purposes of discussion will be employed here.

Regression Methods

Regression schemes are statistical approaches to the evaluation of growth data utilizing:

1. the coefficient of correlation (r or R), the magnitude of which shows the extent of linear concurrence of two or more variables,

2. regression ("prediction") equations which are algebraic descriptions of the relationship of a dependent variable measured at one time to one or more independent variables obtained from the same individual at another, earlier time.

The regression equation is usually not generated unless a statistically and clinically significant coefficient of correlation is found first.

Björk and Palling (1953) attempted to estimate the age changes in overjet and sagittal jaw relation between ages 12 and 20 for 253 Swedish males. They found that the correlation between the degree of overjet at age 12 and the change in overjet from 12 to 20 had a statistically significant--but clinically useless-value of -0.21. In addition, they observed that the degree of maxillary and mandibular prognathism as measured at 12 years of age by the angles S-Na-A and S-Na-Pog respectively bore "no" relation to the changes occurring between 12 and 20. They concluded that, "The degree of prognathy in either jaw does not therefore provide any clue to the future prognathic development."

Based upon correlation coefficients derived during a series of studies dealing with the prediction of changes in certain craniofacial dimensions in a sample of boys from five to eleven years, Meredith (1959) concluded that:

> . . . the size of the child at four or five years of age gives no clinically useful information regarding the rate at which he will grow during the ensuing years of childhood.

Harvold (1963) examined the predictability of the rate and the amount of mandibular growth occurring between six and twelve years of age in fifty-five boys. His conclusions paralleled Meredith's.

Beattie (1963), in an unpublished thesis, obtained correlation coefficients for mandibular size between 6 and 18 years of age for

males and females. Values were high and ranged between 0.73 and 0.94. However, he made no claim for the clinical utility of these findings, inasmuch as they were size-size, rather than size-gain, coefficients.

Time-Series Methods

Growth may be considered as a series of changes occurring with time, and correspondingly, may be evaluated by time-series analysis in an effort to "extract in a mathematical form the fundamental nature of a process as it relates to time" (Hirschfeld and Moyers, 1971). If need be, the equations obtained via the time-series analysis may be "smoothed" to "give representative or average values to the parameters of a previously derived time-series equation." The component parts of a time-series may be listed: 1) trend or long-term movement, 2) oscillations about a trend, 3) cyclic or periodic events, and 4) random (unsystematic) components.

Hirschfeld and Moyers felt that this method may hold great promise for an accurate individual forecast because the parameters of the time-series equation could be derived for each individual from a series of cephalograms for that individual. Lacking a series of cephalograms for the individual, parameters derived as mean values for an appropriate population could be substituted for individualized parameters and a prediction, albeit somewhat less accurate, could be obtained even from a single cephalogram.

To date, this method has apparently been applied to only one small sample of ten children examined from six to sixteen years of age (Hirschfeld and Moyers, 1971). The statistical analysis (via

Student's t-test and the Chi square test) of the data obtained from this study indicated that the time-series method, when compared with the regression method, may be capable of providing more accurate predictions. In light of the fact that the details of this method have not yet been published, that its accuracy has not been precisely characterized, and that it has not been validated on a large sample, Hirschfeld and Moyers' enthusiasm may be somewhat premature. Extrapolation of the results of previous workers such as Johnston (1968), Balbach (1969), Ballrick (1971), and Walker and Kowalski (1971) seems to cast doubt upon our ability to obtain the appropriate individual or population coefficients required for the time-series equations. In addition, Reukema (1971), in his evaluation of the so-called "Tweed growth trends," (vide infra) has noted that the individual pattern of growth bore no consistent relation to growth trends inferred from observations obtained over an eighteen-month period. Thus, it may be said that past growth or present attainment have not proved to be reliable indicators of future patterns of facial growth.

Hereditary Methods of Growth Prediction

In its simplest form, "hereditary" prediction is based on the assumption that an individual's pattern of growth will mimic that already demonstrated by parents and siblings. Often, predictions based on pedigree take the form of rather broad generalizations, rather than precise mathematical statements.

The hereditary methods described by Wylie (1944), Curtner (1953), and Wasson (1963) are non-mathematical schemes in which lateral cephalograms of parents and offspring are compared in an effort to pre-determine (i.e., forecast) the adult faces of the children. Perhaps because of the influence of Brodie's pattern concept, Wylie was unable to explain the lack of resemblance seen for angles comprising the facial polygons of parents and offspring. Curtner, in a study of the cephalometric similarities between parents and offspring in five families, felt that the skull of each child in four of the families generally resembled more closely that of one of the parents, and that the offspring in the fifth family appeared to be composites of both parents. Based on these data, Curtner claimed that, "It appears possible to predetermine the adult face in most children. . ." Apparently, the goal of Curtner's scheme was to provide the clinician with a general impression rather than with an actual drawing of the child's face in adult form.

Wasson more modestly claimed an accuracy of 58.9 percent in an application of the Sassouni archial analysis to uncover similarities and differences in facial pattern; he did not define the meaning of the word "accuracy."

Pelle (1971) derived multiple correlation coefficients for nineteen linear and thirteen angular measurements. His data were obtained from lateral cephalograms for twenty-four pairs of male siblings and twenty-one pairs of female siblings. Prediction equations for the future size of $\angle$ A-Na-B derived from data for the

sibling-pairs were found to be no more accurate than adding an estimate of the mean change to each individual's initial ∠ A-Na-B.

It should not be inferred that there is no genetic component in the attainment of craniofacial form. Indeed, it has been shown by, among others, Hunter (1965), Hunter and associates (1970), and Brown (1973) that statistically significant intra-familial correlations do exist. Moreover, Harris and associates (1975) have argued that these correlations could form an important element in an improved approach to prediction. Unfortunately, only Pelle (1971) has presented specific equations combining individual and familial data (siblings), and these were only minimally efficient. Perhaps other combinations will prove more useful.

The present status of the hereditary approach to growth prediction may be summarized by stating simply that despite their "common sense" appeal, they have failed to achieve widespread clinical usage or acclaim because they generally do not lead to precisely quantifiable predictions.

Experiential Methods

The experiential method is an attempt by an individual to define and systematize personal clinical observations or experiences which he has found useful and which he feels others may find equally useful. Although more precise, they are in many ways similar to "rules of thumb."

One of the first of this type, the Tweed "Growth Trends" (Tweed,

1963) classified the individual growth pattern during the mixed dentition stage. From serial cephalograms taken during an eighteen month pre-orthodontic observation period, measurements of the size and change in magnitude of ∠ A-Na-B are recorded. Based upon these measurements, growth is classified into three types (A, B, and C) with various subdivisions depending upon the anteroposterior maxillo-mandibular relationship. The assumption is made that the growth trend observed during this period will persist during the development of the permanent dentition, and treatment is planned accordingly.

Reukema (1971), in an unpublished thesis, tested the Tweed growth trend theory on a longitudinal sample of eighty-four children. He found the theory to be statistically unreliable and felt that decisions regarding the treatment planning of mixed dentition cases should not be influenced by it. Reukema also strongly concurred with an earlier statement of Johnston (1968) that ". . . it would seem highly improbable that any one measure could ever contain enough information to be of predictive significance." With regard to maxillo-mandibular relationship, Reukema found evidence of "an overall tendency of growth toward type C [increasing mandibular prognathism], when not random."

Over the last two decades, Ricketts has presented the orthodontic specialty with four different methods for cephalometric prediction--the earlier "static" and "dynamic" syntheses (both long and short methods) and, more recently, the "arcial" method. The static and dynamic syntheses were introduced in a series of articles spanning the years 1957 to 1961. The static synthesis and the long

method of dynamic synthesis were introduced in 1957; the long method was simplified and appeared, transformed, in 1960, as the "short" method (1960c). The two types of syntheses were similar, but the static synthesis was intended for application only in cases where no further growth was expected, and, therefore, only changes in alveolar processes and tooth position due to treatment could reasonably be anticipated. The static synthesis was, in essence, a cephalometric tooth set-up within the framework of stable basal bones. In contrast, the dynamic syntheses had as their goal the prediction of the combined effects of growth and treatment on the individual growing child one to three years in advance. Cognizant of the wide variability of human form, growth and development, Ricketts was of the conviction that each orthodontic treatment should be tailored--in goals and in treatment mechanics--to the individual. By 1960, he viewed the "dynamic synthesis" as an indispensable adjunct in this pursuit, and implied that failure to execute an individual prediction for every case could be "considered . . . neglect of the patient."

Ricketts earliest publications stem from his interest in the biology of the temporomandibular joint. Accordingly, it is not surprising that many of Ricketts' concepts of growth prediction are based upon the behavior and morphology of the mandible with special emphasis on the temporomandibular joint. Ricketts' basic premise was that present form is a measurable sign of biological processes which have existed, and which will continue to exist in the future. The morphological signs which Ricketts considered to be of prime

importance may be listed: 1) mandibular plane angle, 2) gonial angle, 3) width of ramus, 4) thickness of condyle, 5) width of symphysis, 6) inclination of condyle, 7) corpus length, 8) coronoid height, 9) occlusal plane, and 10) antegonial notching.

With the exception of a validation by Balbach (1969, vide infra), no precisely defined system for analyzing these ten characteristics has been published. Rather, each characteristic is to be evaluated subjectively by the clinician, and a total "impression" of their probable effect on lower face growth figured into the forecast. The earlier Ricketts synthesis employed estimates of average linear changes derived from several different investigations. A study of one hundred non-orthodontic cases and two hundred and fifty treated cases yielded insights into the effects of growth alone and growth in combination with treatment. Growth alone accounted for a forward positioning of nasion (on the sella-nasion plane) of approximately one millimeter per year, reduction of SNA by two degrees during an observed growth period similar to that occurring during treatment, dropping of PNS parallel to pterygomaxillary fissure, and approximately 2.5 to 3 millimeters of mandibular growth along the Y-axis (sella-gnathion) per year. In the maxilla, treatment resulted in distal molar movement, changes in amount and direction of growth, and distal movement of A-point (as much as eight millimeters) when incisor retraction with lingual root torque, headgear, and Class II elastics was accomplished. The most notable effects of treatment upon the lower jaw were: 1) mandibular rotation resulting in a

change of growth direction, and 2) tipping of the occlusal plane. Growth changes with treatment were further characterized in a large study of one thousand treated clinical cases from Ricketts' private practice.

It should be noted that execution of the dynamic synthesis as outlined by Ricketts is a stepwise procedure (which may be carried out by hand or by the computer), and consequently the accuracy (or inaccuracy) of the net result is partly dependent upon the accuracy of each intermediate step.

Claims of accuracy for the short-range dynamic synthesis have appeared from time to time, ranging from (1957) ". . . [accuracy to] within the width of a pencil line" and "sensibly accurate in ninety percent of the cases" to a 1960 statement, "At the clinical level this procedure yields a rough estimate of conditions most likely to occur." In 1961, Ricketts conceded that additional statistical data should be compiled on the dynamic synthesis to make it "simpler and more foolproof."

In a summary of his more recent observations concerning mandibular growth (1972a, b, c, d) and its application to cephalometric prediction, Ricketts presented the theory of "arcial" growth of the mandible. The arcial theory has not been well-defined but apparently constitutes a system of geometry used to duplicate empirically the growth-rotation of the mandible seen with metallic implants (Björk and Skieller, 1972). Ricketts believed that integration of this theory into the technique of growth prediction should permit accurate forecasts over a longer range (five to fifteen years)

(1972d) than in his original method (one to four years). However, the complex geometry attendant to an arcial forecast rendered growth prediction a considerably more difficult procedure than the older technique. A logical solution to this difficulty seemed to be the use of computer technology for some of the laborious manual procedures. At present, long-range arcial growth forecasts are available commercially through Rocky Mountain Data Systems (RMDS), Inc. It is interesting to note that, to date, only a rather superficial summary of the mechanics of computerized arcial forecast has appeared in the literature (Ricketts et al., 1972).

The salient characteristics of the RMDS method have been summarized by Greenberg (1972):

> The computerized scheme of growth prediction is specifically designed to minimize measurement error related to the construction of growth forecasts. Once programmed with key cephalometric points, the computer accurately analyzes the data in the form of linear and angular measurements which are summarized on print-out sheets. Using a sophisticated "polar-grid" coordinate system, the computer also advances these key cephalometric points the predetermined magnitude and direction to form an outline to which the technician adds the anatomy for the prediction.

Although similar to the basic framework presented in 1957, the current computer program is "individualized" so as to adjust the added increments according to the patient's race, age, sex, and overall facial size.

The predictive accuracy of the computerized method has not, as yet, been characterized meaningfully by its proponents. Rather, statements such as, ". . . no claim for positive dependability has ever been made" and ". . . [results are] at least ninety percent accurate, seventy percent of the time in upper face height" are felt

to suffice. Fortunately, we are not totally dependent upon these vague characterizations, for independent assessments of various prediction methods have been made, and inferences drawn from them may apply to the Ricketts methods.

Johnston (1968), from evidence obtained in a multivariate examination of prediction, observed that although the absolute amount of growth during a prediction interval may be large, the change in form--or, more precisely, changes in form which deviate from the mean--may often be quite small. Accordingly, when compared to the magnitude of the change that could be wrought by treatment, the deviations from the mean pattern may be a relatively insignificant component of the overall change. Moreover, the accuracy of cephalometric prediction, according to Johnston, is limited absolutely (and inescapably) by error inherent in the technique itself. In view of the general lack of successes seen for methods designed to predict individual changes, Johnston (1968) has concluded that the addition of mean increments to the individual is essentially the best that can presently be done. He also observed that, other considerations aside, a prediction of growth and treatment together may prove to be a self-proving hypothesis in the hands of a skilled orthodontist who utilizes clinical feedback to guide the outcome of treatment.

Balbach (1969), in a validation of the predictive significance of Ricketts' mandibular morphologic indicators, sought to investigate the "relationship of the morphology of the mandible to the amount and direction of mandibular growth." He studied a combination of linear

and angular measurements of mandibular morphology and position at seven and eleven years for males. Multivariate analysis was used to combine mathematically the various mandibular characteristics and generate multiple regression equations. With respect to amount and direction of growth, Balbach concluded that no statistical support could be found for the hypothesis that mandibular characteristics, either individually or in combination, provide information upon which to base an accurate prediction of changes in the occlusal position of the mandible.

Greenberg (1972), compared the accuracy of three approaches to prediction: 1) the assumption that no change would occur over a five year period, 2) the assumption that the mean change provides the best forecast, 3) the assumption that one or both of the Ricketts methods (i.e., Ricketts synthesis executed by hand or by computer) provides the best forecast. Statistical analysis of nine linear and four angular measures for one hundred author-predicted cases and twenty computer predicted cases (a subsample of the one hundred author predictions) provided the basis for these conclusions (Greenberg, 1972):

1. The use of the Ricketts synthesis for the prediction of changes attributable only to growth is somewhat more accurate than an assumption of no change and less accurate than adding an estimate of the five-year mean change.

2. For any non-trivial prediction (craniofacial relationship), the Ricketts synthesis, executed by hand or by computer, can not be shown to be of sufficient efficiency to be of clinical significance.

3. The magnitude of inherent cephalometric error is sufficient to mask changes attributable only to growth.

4. A decision to employ the Rocky Mountain Data Systems, Inc. prediction scheme must be based on factors other than its prediction efficiency; namely, its undoubted heuristic significance and its considerable utility in patient education.

Before discussing the newest prediction scheme (the Johnston Forecast Grid) it may be helpful to review briefly the highlights in the evolution of cephalometric prediction which led to its development.

At the opening of the cephalometric era, the pattern concept predominated. Growth was viewed as being proportional, hence there would be nothing to predict. Yet, the investigations of Björk, Coben, Lande and others soon established the validity of changes in the growth pattern of the population on the average and, even more so, for the individual. Early research into cephalometric prediction had as its goal the forecasting of changes in pattern for the individual. A notable example of an attempt at individualized forecasting is the Ricketts dynamic synthesis. However, work by Björk, Johnston, Balbach, Greenberg, and others pointed out that true individualization, i.e., the ability to predetermine the magnitude, direction and timing of growth for a specific person was not feasible at present, and indeed, considering the nature of the problem, might never be possible. Hence, individualization as applied to contemporary cephalometric prediction schemes means mostly that the forecast adds small mean changes to an initial cephalogram of the individual. According to Greenberg (1972),

even an individualized arcial forecast behaves essentially like a mean-change expansion. Given this statement of apparent reality, the problem of forecasting reduces to a question of how the mean change expansion of the initial cephalogram should be accomplished. Until recently, the choices were only two: The forecast was executed either by means of hand-drawn geometrical constructions of varying complexity, or by computer technology. These limited choices have hampered the clinical application of cephalometric prediction for many reasons. Some interested clinicians did not understand or did not care to master the geometric steps of the hand-drawn forecast procedure, while others did not have the time to execute personally or supervise the execution of the forecast. Still others did not relish the considerable expense which a demonstration of the abilities of the commercial forecast would entail.

In view of the limitations of the existing techniques and the current state of the art, Johnston (1975) introduced a method which should, to a first approximation, duplicate the computer graphics used by RMDS, and which would, at the same time, be simpler, more direct, and less costly to use. This method (termed a "forecast grid") employs a printed array of graticules, the size and angulation of which correspond to estimates of the average amount and direction of growth for a series of cephalometric points. Although transformed meshes (DeCoster, 1931 and Moorrees, 1953) and templates (Harris et al., 1963) have been employed in cephalometric analysis, the use of a grid for growth predictions, perhaps, is a new application of such coordinate systems. This device is used to relocate ("grow") a set of landmarks which, in

their new positions, serve as a framework for the addition of detailed anatomy by regional superimposition. The net result is a method by which the orthodontist can enlarge any cephalogram by the mean amount called for by the length of the prediction interval. The grid relocates five hard tissue structures (nasion, posterior nasal spine, upper first permanent molar, and A and B points) and one soft tissue landmark (tip of the nose). Behavior of these points was inferred from several sources: Vectors for A, B and M were obtained from descriptive templates prepared by Harris and asscoiates (1963), whose sample consisted of Ann Arbor school children participating in the University of Michigan School Growth Study. Behavior of N and P was based on reports by Ricketts (1957, 1971). The increments for the nose were inferred independently by Johnston (1975). The new location of pogonion, based on a construction rather than movement along a graticule, is also predicted, and instructions are provided for the construction of the soft-tissue profile. The grid produces a flattening of both the profile (after Björk, 1953) and occlusal plane, as well as a mesial migration of the dentition.

Use of the earliest versions of the Johnston Forecast Grid assumed every year of prediction to result in the same amount of change. However, it is well-known that growth is not a smooth process, but rather is characterized by varying rates (Beattie, 1963, for example). Therefore, rather than altering the grid itself, a chart was constructed which listed individualized numbers of grid-units to be added according to starting age, years of prediction, and sex (see Johnston, 1975, Table II, p. 257 and Figure 2 of the present communication).

A recent review of contemporary prediction schemes by Schulhof and Bagha (1975) compared the predictive accuracy of the Johnston Grid, a so-called S-N average increment method, the Ricketts short-range method and the RMDS program. The material for the study consisted of fifty cephalometric series covering, on the average, the period from 6.25 (range, 5 to 16) to sixteen (range, 13-26) years of age. The mean period of growth prediction was stated to be 9.42 years. The results of the comparison were expressed in terms of root mean squared errors and percentage accuracy (a descriptive statistic which was left unexplained). The Johnston Grid employed was a prepublication xerographic reproduction and did not include the individualization table.

Schulhof and Bagha concluded that the methods differed and ranked them in order of decreasing accuracy as follows: RMDS program, Ricketts short-range, S-N average increment, and Johnston Grid. However, many aspects of this study may be questioned. It is not explained how the predictions were handled during non-growing years (e.g., how many units of growth were used for the patient who was twenty-six at the time of final records?) The Johnston Grid grows A point 1.25 millimeters per year. For a period of 9.42 years of prediction, 11.8 millimeters of growth should obtain, yet Schulhof and Bagha list a value of 14.6 millimeters (Table I, p. 270, Schulhof and Bagha, 1975). Similarly, at 2.0 mm/year the nose should grow 18.8 millimeters; their published value is twenty millimeters. Also notable is the inclusion of average growth values for "Xi" and "B6," points which are not even included on the grid. Thus, the errors in this table, the unclear characterization of the sample and

inconsistencies in some of the statistics cast doubt on the inferences which may be drawn from the results presented in this article.

In view of the similarity between the Rocky Mountain Data System computerized prediction method and the Johnston Forecast Grid, it is remarkable that they should differ markedly in accuracy as has been reported by Schulhof and Bagha (1975). It will, therefore, be the purpose of the present investigation to characterize independently the accuracy of the grid on a large sample over varying prediction intervals, and to compare the results with those previously published by Schulhof and Bagha (1975) and by Johnston (1975).

MATERIALS AND METHODS

Sample

The cephalograms utilized in this study were obtained from the files of the Bolton-Brush Growth Study Center at Case Western Reserve University, Cleveland, Ohio. A sample of one hundred orthodontically-untreated subjects (fifty males and fifty females) was selected at random. For this study, "random" meant that the selection was in no way based on any characteristic of the craniofacial skeleton before, during, or after the period of growth for which the prediction was intended. Each subject had a lateral cephalogram taken in occlusion at two of several different ages. The distribution of the sample by ages, sex and molar classification (Angle) is indicated in Table I. Classification by Angle molar relationship does not necessarily imply a corresponding skeletal pattern. It should be noted that the number of years of prediction for both males and females varied from two to ten years, in two-year increments. The distribution was selected to test the validity of the forecast grid over varying intervals covering those ages during which most orthodontic treatment is rendered.

Johnston Forecast Grid

The prediction method whose accuracy is examined here is the so-called "Johnston Forecast Grid." Several forms of this grid have been devised, the one examined here coming from p. 255 of Johnston, 1975. It is reproduced here in Figure 1.

TABLE I

DISTRIBUTION OF BOLTON SAMPLE OF 100 PATIENTS
BY SEX, INITIAL AND FINAL AGES,
AND MOLAR RELATIONSHIP

Molar Relationship at Time of Final Cephalogram	Males					Females					Total
	8-18 Yrs.	10-18 Yrs.	12-18 Yrs.	14-18 Yrs.	16-18 Yrs.	6-16 Yrs.	8-16 Yrs.	10-16 Yrs.	12-16 Yrs.	14-16 Yrs.	
Class III	. .	. .	. .	. .	1	1	. .	. .	. .	1	3
Class III Tendency	. .	. .	. .	. .	1	. .	. .	1	1	. .	3
Class I	5	5	4	3	5	5	5	5	5	7	49
End-to-End	2	3	4	4	3	1	3	1	2	. .	23
Class II	3	2	2	3	. .	3	2	3	2	2	22
Total	10	10	10	10	10	10	10	10	10	10	100

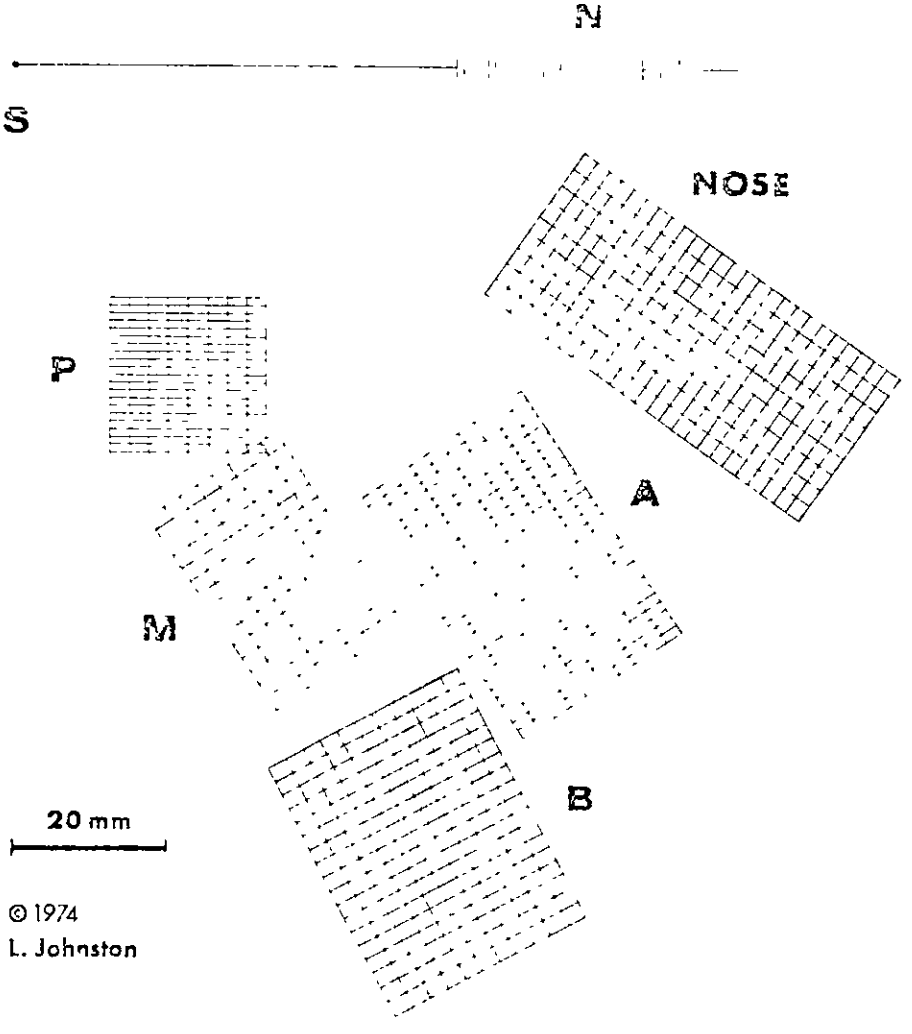


Figure 1.--Johnston Forecast Grid
(after Johnston, 1975)

Technical Details

The lateral cephalograms used in this study were obtained with a Broadbent-Bolton cephalometer using a source-object distance of sixty inches; no soft-tissue shields were used. Tracings and growth forecasts were made in pencil (2H) on .003 inch frosted matte acetate. Linear measurements, obtained through the use of dial vernier calipers (modified Helios dial calipers, catalogue no. 382, Dental Corporation of America, Washington, D. C.), were rounded to the nearest tenth of a millimeter. Reference lines for obtaining error measurements were drawn with the aid of a drafting machine (Vemco; Model 3300, V & E Manufacturing Company, Pasadena, California).

Growth Forecasts

Prior to performing the growth forecasts, the author received a brief (less than one hour) instructional session from the originator of the forecast grid. Following this session, the one hundred forecasts were performed according to the published instructions (Johnston, 1975).

Each of the initial cephalograms was traced by the author. Seven landmarks necessary to execute the grid prediction were located and marked on the initial tracing (Figure 2, Step A):

1. N--nasion;
2. P--posterior nasal spine;
3. Nose--tip of the nose;

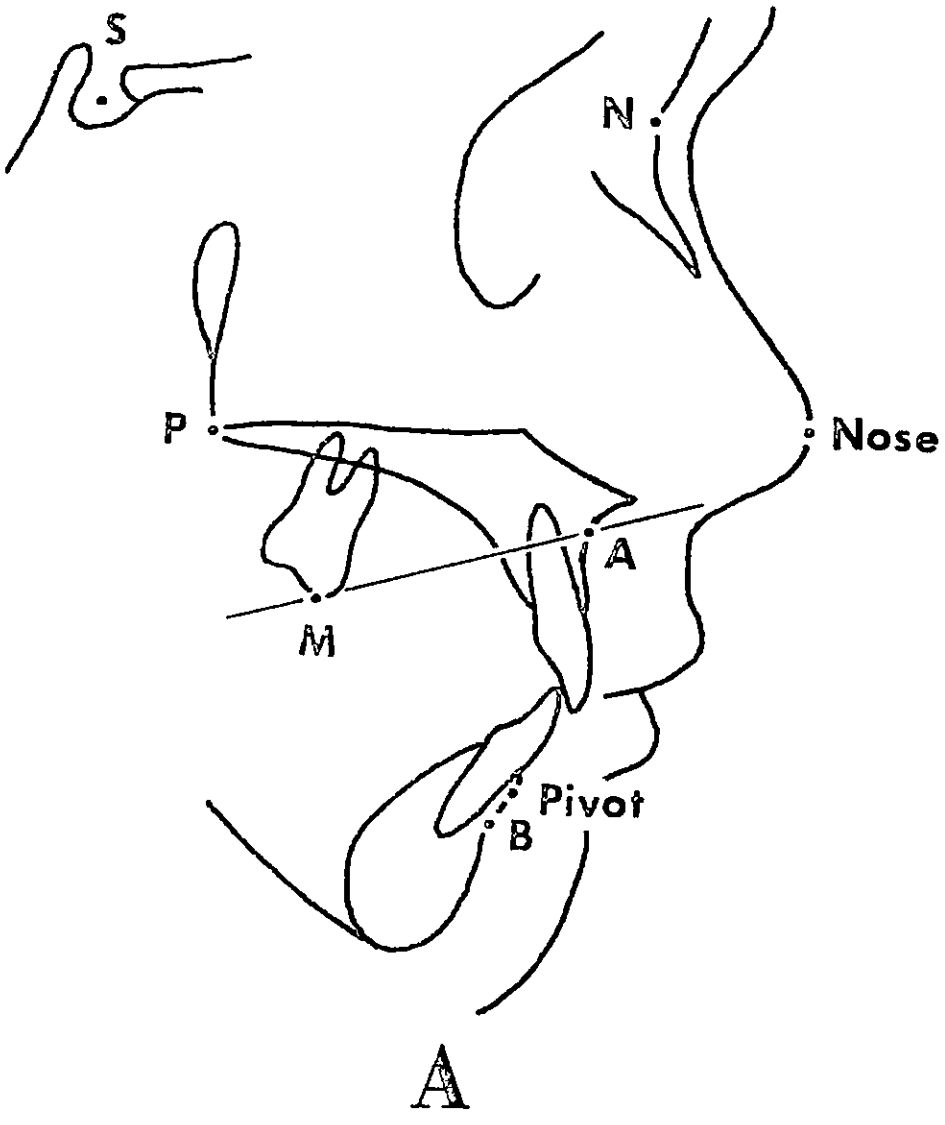
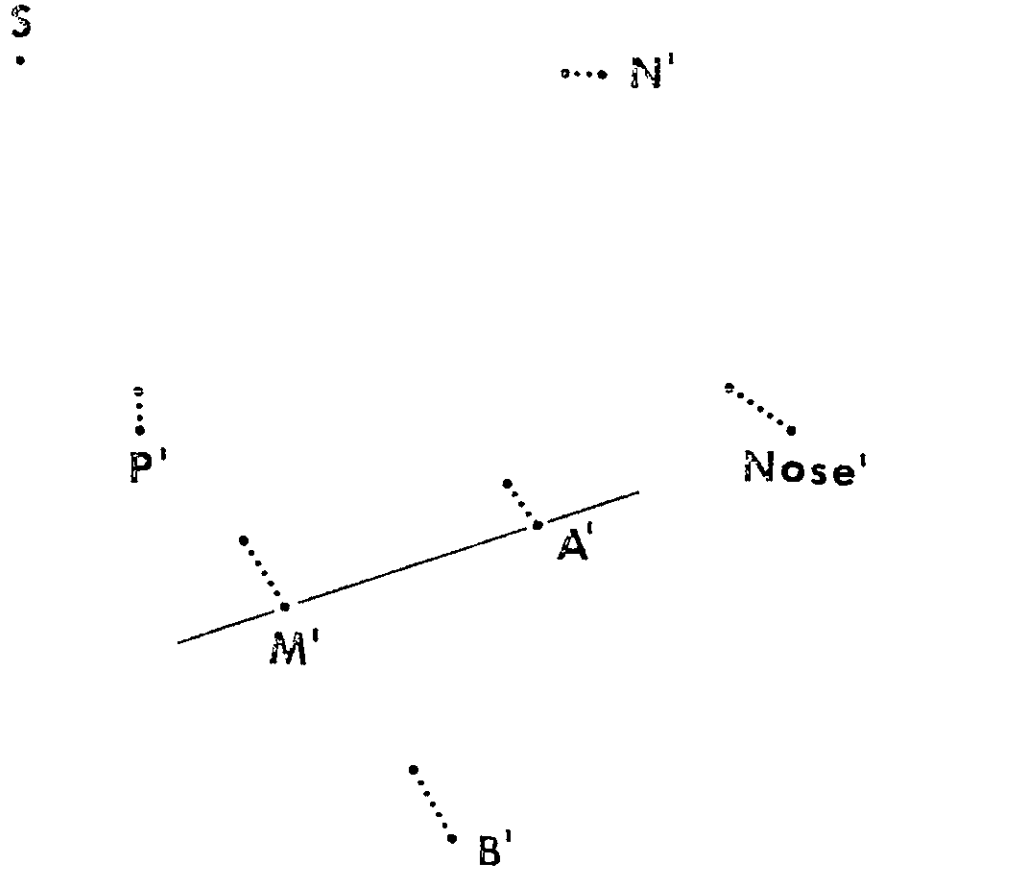


Figure 2.--Steps performed by the author to execute Johnston Grid predictions.

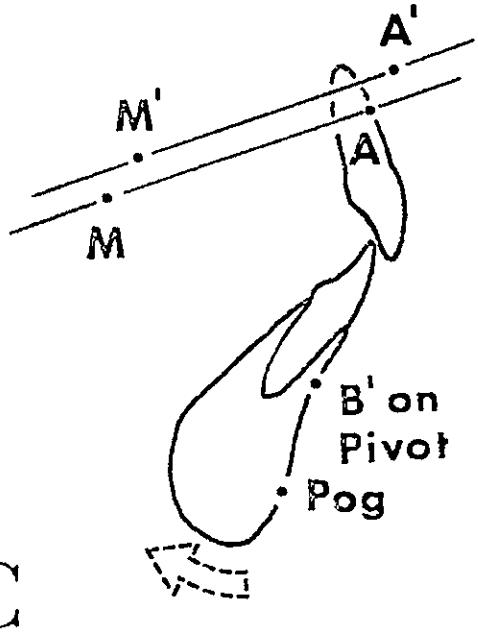
Step A.--Tracing of the initial cephalogram with necessary landmarks located and labelled, and plane M-A drawn.

Step B.--Original points relocated, and plane M'-A' drawn.

Step C.--Relocation of bony chin (pogonion), by construction.



B



C

4. M--any point on the crown of the maxillary first permanent molar;

5. A--subspinale;

6. B--supramentale;

7. S--sella.

A line was drawn connecting points M and A, and a point 0.5 mm above B for each grid-unit of prediction (the so-called "pivot" point) was marked on the initial tracing. For example, for six units of growth, pivot point would be located 3.0 millimeters above B along the outline of the mandibular symphysis. Then, a second piece of acetate (on which the prediction was to be made) was placed on top of the initial tracing, and the seven landmarks were copied. By orienting on sella-nasion and registering on sella, the "prediction" acetate was then superimposed on the forecast grid (Figure 1), the points relocated the appropriate number of grid-units called for in the individualization chart (Table II, after Johnston, 1975). The relocated points are designated with primes (e.g., M' for relocated M). A line connecting M' and A' was drawn on the prediction (Figure 2, Step B). The location of pogonion' was determined by placing the prediction over the initial tracing with B' registered on pivot point and rotating the prediction until M'-A' paralleled M-A. The outline of the symphysis (including pogonion) was then traced (Figure 2, Step C). For purposes of this study, the soft tissue profile, incisors, and incidental anatomy were not forecast.

TABLE II

TABLE TO INDIVIDUALIZE JOHNSTON FORECAST GRID PREDICTIONS ACCORDING TO STARTING AGE, YEARS OF PREDICTION, AND SEX (after Johnston, 1975)

Starting Age, Males

Years of Prediction

Starting Age, Males	10	9	8	7	6	5	4	3	2	Starting Age, Females
	9	9	8	7.5	6.5	6	5	3.5	3	6
		7.5	7.5	6.5	6	5	4.5	3.5	2	7
16	1		6	6	5	4.5	4	3	2	8
15	2	2.5		5.5	5.5	4.5	3.5	3	2	9
14	2.5	3.5	4		4.5	4	3	2.5	2	10
13	2.5	3.5	4.5	5		3.5	3	2.5	1.5	11
12	2	3.5	5	5.5	6		2.5	2.5	1.5	12
11	2	3	4.5	6	6.5	7		2	1.5	13
10	2	3	4.5	5.5	7	8	8.5		0.5	14
9	2	3	4.5	5.5	6.5	8	9	9.5		
8	2	3	4	5.5	6.5	7.5	9	10	10.5	
7	2.5	3.5	4	5	7	8	9	10.5	11.5	12
6	3	4	5	6	7	8	9	10.5	12	12.5	13
	2	3	4	5	6	7	8	9	10	11	12

Years of Prediction

Because of relative magnitude of technical error, one-year forecasts are not recommended.

Forecasting Error

Upon completion of each prediction, the second cephalogram in the series was traced so that the accuracy of the prediction could be judged. The predictions were compared with the actual outcome for each subject by superimposing them on the sella-nasion plane and registering on sella. The actual location of the seven landmarks was transferred to the same sheet of acetate upon which the prediction had been performed. In this manner, a single tracing was obtained for each subject containing the predicted and actual position (relative to the sella-nasion plane) for the seven landmarks. For each pair of points (predicted and actual), an abscissa and ordinate were drawn (perpendicular and parallel to sella-nasion, respectively) so as to permit the measurement of error of the deviation of predicted from actual (Figure 3). Three measurements were taken for each pair:

1. Horizontal error (X)--the error in a horizontal direction parallel to sella-nasion plane;
2. Vertical error (Y)--the error in a vertical direction perpendicular to sella-nasion;
3. Total error (T)--the absolute distance between each pair of points.

For the horizontal and vertical errors, signs were assigned so that a positive error signifies a prediction which proved too large; a negative error, a prediction which was too small.

Technical Error

In order to estimate the contribution of technical error to prediction, a sub-sample of twenty final cephalograms was selected

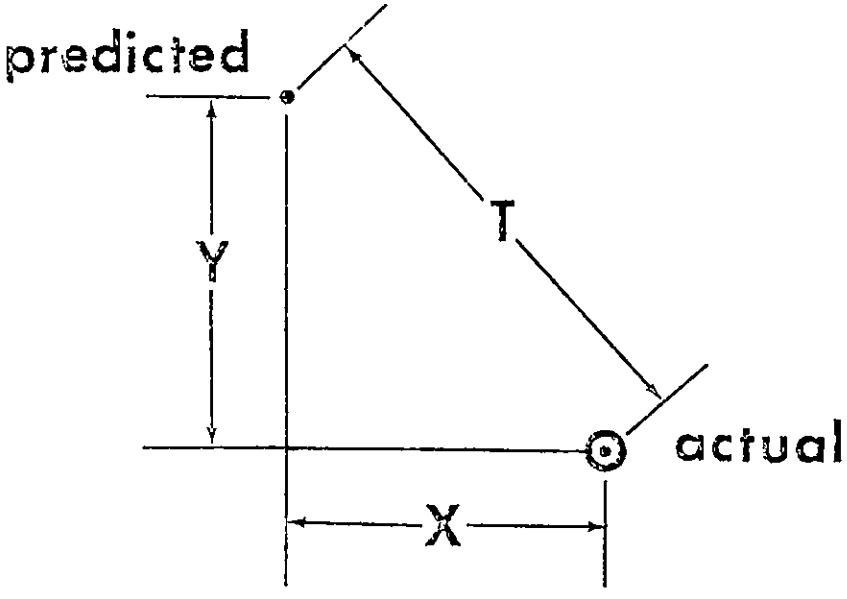


Figure 3.--Components of error--
Horizontal (X), Vertical (Y)
and Total (T)

(with the aid of a table of random numbers) from the sample of one hundred subjects. Each of these twenty cephalograms was retraced. As determined by the toss of a coin, one tracing of each pair was designated the "prediction" (the other tracing becoming the "actual") and the differences analyzed in the manner described previously. Thus, the double-determinations constituted an additional prediction-interval (0 years) and, as such, may be regarded as providing an estimate of the minimal prediction error.

Statistical Methods

The following descriptive statistics were calculated for each of the measurements:

1. The average error: The sum of the signed differences between predicted and actual, divided by the number of differences.

2. The average absolute error: The sum of absolute values of the differences between predicted and actual, divided by the number of differences.

3. The root mean squared error: The square root of the sum of squared differences between predicted and actual, divided by the number of differences.

$$RMSE = \sqrt{\frac{\Sigma(\text{Predicted location} - \text{Actual location})^2}{N}}$$

The calculations were performed with the assistance of a portable electronic calculator (Melcor, Model 400; Melcor Electronics, Farmingdale, New York).

FINDINGS

Average Error, Average Absolute Error, and Root Mean Squared Error

Average error, average absolute error, and root mean squared error, broken down into horizontal (X), vertical (Y), and total (T) components, for one hundred author-prepared Johnston Grid predictions are shown in Tables III, IV, and V, respectively. In addition, total root mean squared errors are presented graphically, by landmark, in Figure 4.

Cephalometric Error

The tracing errors found in the replication of twenty tracings are shown in Table VI. These measurements are a reflection of the author's consistency in tracing and locating cephalometric landmarks. The total (T) root mean squared errors from the double determinations may be considered the accuracy of predictions for zero years. Accordingly, the technical errors are graphed in Figure 4 at 0 years. Errors for real predictions (i.e., those conducted over a time-interval greater than zero) may be evaluated using the tracing errors as a baseline for comparison. Combined root mean squared tracing error was consistently less than one millimeter, with the exception of total RMSE for posterior nasal spine (P).

TABLE III

AVERAGE ERROR

(in millimeters)

Point	Error Component	Prediction Interval									
		Males					Females				
		16-18 Yrs.	14-18 Yrs.	12-18 Yrs.	10-18 Yrs.	8-18 Yrs.	14-16 Yrs.	12-16 Yrs.	10-16 Yrs.	8-16 Yrs.	6-16 Yrs.
N	X	-0.4	-0.9	-0.2	0.9	0.5	-0.1	0.5	0.2	0.4	0.7
	Y	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
	T	0.4	0.9	0.2	0.9	0.5	0.1	0.5	0.2	0.4	0.7
P	X	-0.2	-0.2	0.5	0.2	0.0	0.1	-0.2	0.0	0.3	0.6
	Y	-0.3	0.9	1.5	1.7	3.0	-0.2	0.4	0.5	0.6	0.8
	T	0.4	0.9	1.6	1.7	3.0	0.2	0.5	0.5	0.7	1.0
M	X	-0.4	-0.3	2.1	1.8	3.1	-0.1	-0.2	-0.3	1.0	2.0
	Y	-0.8	-1.2	-1.0	0.1	-1.6	-0.7	-1.2	-1.7	-3.0	1.9
	T	0.9	1.2	2.3	1.8	3.5	0.7	1.2	1.7	3.1	2.7
A	X	-0.6	-1.9	-1.2	-0.8	-0.2	-0.1	-0.3	-0.8	-0.2	0.8
	Y	-0.5	-0.7	0.9	0.8	0.1	-0.2	0.0	0.1	-1.3	-1.4
	T	0.8	2.0	0.2	1.2	0.3	0.2	0.3	0.9	1.4	1.6
B	X	-1.0	-2.0	0.6	1.1	1.4	-0.2	0.0	-1.0	0.4	0.1
	Y	-0.9	-0.4	1.7	3.7	1.3	-0.3	0.4	1.2	0.1	0.7
	T	1.8	2.0	1.8	3.8	2.0	0.4	0.4	1.6	0.4	0.8
NOSE	X	-1.3	-2.9	-1.3	-1.2	-0.2	-0.7	-0.3	-1.5	-1.0	0.2
	Y	-0.4	0.5	1.6	3.2	2.4	-0.7	0.4	0.4	0.2	1.0
	T	1.3	2.9	2.1	3.5	2.5	1.0	0.5	1.6	1.0	1.1
POG	X	-1.0	-2.0	2.5	1.5	1.3	-0.4	-0.8	-1.9	-0.7	-1.3
	Y	-1.4	-1.1	1.5	3.3	1.8	-0.5	0.8	0.1	-0.9	1.4
	T	1.7	2.3	1.5	3.7	2.2	0.7	1.2	1.9	1.2	1.9

TABLE IV

AVERAGE ABSOLUTE ERROR

(in millimeters)

Point	Error Component	Prediction Interval									
		Males					Females				
		16-18 Yrs.	14-18 Yrs.	12-18 Yrs.	10-18 Yrs.	8-18 Yrs.	14-16 Yrs.	12-16 Yrs.	10-16 Yrs.	8-16 Yrs.	6-16 Yrs.
N	X	0.5	1.1	0.5	0.9	1.5	0.2	1.0	0.4	0.5	0.8
	Y	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
	T	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
P	X	0.2	0.7	0.6	1.4	1.6	0.2	0.6	0.7	0.4	1.1
	Y	0.9	1.2	1.6	2.0	3.0	0.3	0.6	0.8	1.2	1.6
	T	1.0	1.4	1.9	2.8	3.7	0.4	1.0	1.3	1.4	2.1
M	X	0.8	0.8	2.7	1.9	4.3	0.3	1.2	1.1	1.6	2.5
	Y	1.3	1.5	1.6	1.8	2.1	0.7	1.9	2.1	3.0	2.5
	T	1.6	1.9	3.3	3.0	5.4	0.8	2.2	2.5	3.6	3.8
A	X	0.8	1.9	0.9	2.0	2.3	0.1	1.4	1.1	1.2	1.5
	Y	1.0	1.2	0.9	1.7	1.3	0.2	1.1	0.9	1.7	2.1
	T	1.5	2.4	1.5	2.8	3.1	0.2	1.9	1.6	2.2	2.9
B	X	1.4	2.2	3.0	3.3	3.9	0.3	2.2	2.0	1.4	2.3
	Y	1.6	2.5	2.6	4.5	2.6	0.4	0.9	2.3	1.7	4.6
	T	2.3	3.7	4.4	6.1	5.4	0.5	2.5	3.3	2.4	5.6
NOSE	X	1.5	2.9	1.7	1.9	1.8	0.8	1.7	1.8	1.8	1.0
	Y	1.1	1.3	2.4	3.7	3.3	0.7	1.2	1.0	1.3	2.2
	T	2.0	3.4	3.2	4.5	4.1	1.2	2.2	2.3	2.3	2.6
POG	X	1.8	2.9	3.3	4.2	4.0	0.6	2.9	2.7	2.0	3.3
	Y	2.3	1.9	2.9	4.3	2.2	0.5	1.5	1.7	1.8	5.0
	T	3.3	3.6	4.7	6.4	5.1	0.8	3.5	3.4	3.1	6.5

TABLE V

ROOT MEAN SQUARED ERROR

(in millimeters)

Point	Error Component	Prediction Interval									
		Males					Females				
		16-18 Yrs.	14-18 Yrs.	12-18 Yrs.	10-18 Yrs.	8-18 Yrs.	14-16 Yrs.	12-16 Yrs.	10-16 Yrs.	8-16 Yrs.	6-16 Yrs.
N	X	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
	Y	. .	. .	. .	. .	. .	. .	. .	. .	. .	. .
	T	0.7	1.5	0.7	1.2	1.7	0.3	1.1	0.6	0.9	1.0
P	X	0.4	0.9	0.8	1.8	2.2	0.3	0.7	1.0	0.5	1.3
	Y	1.1	1.3	2.1	2.4	3.3	0.4	0.8	1.1	1.6	1.9
	T	1.2	1.5	2.2	3.0	4.0	0.5	1.1	1.5	1.7	2.4
M	X	1.1	1.1	3.2	2.9	5.7	0.4	1.7	1.5	2.2	3.1
	Y	1.6	1.7	2.1	2.1	2.7	1.0	2.4	2.4	3.5	2.9
	T	1.9	2.1	3.8	3.6	6.3	1.0	2.9	2.8	4.1	4.2
A	X	1.2	2.5	1.2	2.4	3.1	0.2	1.7	1.4	1.5	1.9
	Y	1.5	1.5	1.4	1.9	1.6	0.3	1.2	1.0	2.2	2.6
	T	1.9	2.9	1.9	3.1	3.6	0.4	2.1	1.8	2.7	3.2
B	X	1.9	3.2	3.8	3.9	5.6	0.4	3.1	2.4	2.0	2.8
	Y	2.1	3.1	3.7	5.6	3.7	0.7	1.2	2.7	2.1	5.7
	T	2.8	4.5	5.4	6.9	6.8	0.8	3.4	3.6	2.9	6.3
NOSE	X	2.2	3.9	1.9	2.3	2.4	0.9	2.3	2.4	2.0	1.3
	Y	1.4	1.6	2.9	4.0	3.7	0.8	1.6	1.3	1.7	2.7
	T	2.7	4.2	3.5	4.7	4.5	1.2	2.8	2.8	2.6	3.0
POG	X	2.5	3.7	4.3	5.2	5.9	0.8	3.7	3.0	2.5	4.0
	Y	3.2	2.3	3.8	5.2	2.8	0.8	1.8	2.1	2.4	6.0
	T	4.1	4.4	5.8	7.3	6.6	1.2	4.2	3.7	3.5	7.3

Figure 4. Root Mean Squared Error--Horizontal (X), Vertical (Y) and Total (T) for Males and Females, in Millimeters :

N, nasion; P, posterior nasal spine; M, upper first permanent molar; A, subspinale; B, supramentale; Nose, apex of nose; and Pog, pogonion.

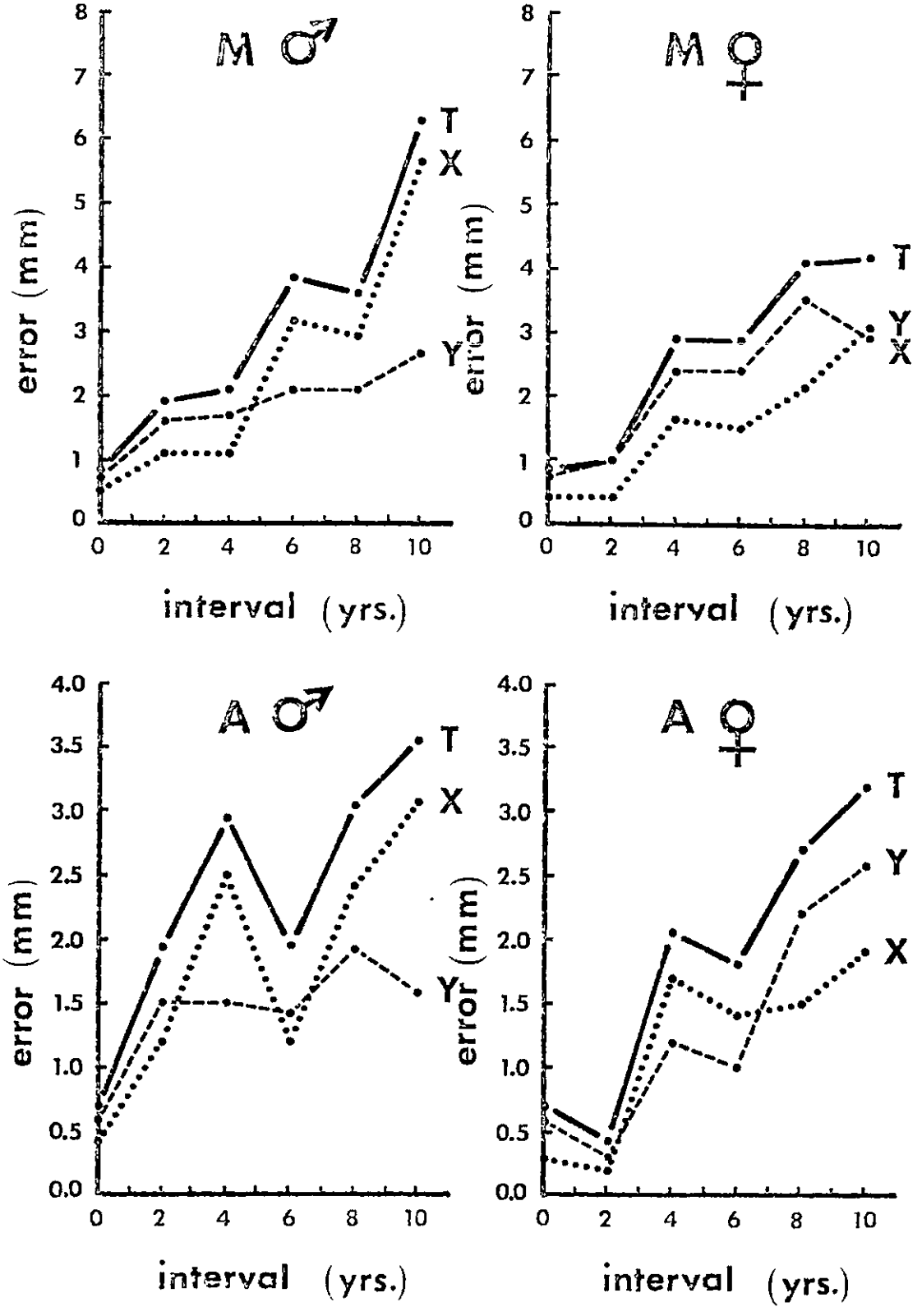

M ♂
M ♀
A ♂
A ♀
error (mm)
interval (yrs.)
T
X
Y
0
2
4
6
8
10
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
1
3
5
7

Figure 4 (cont.)

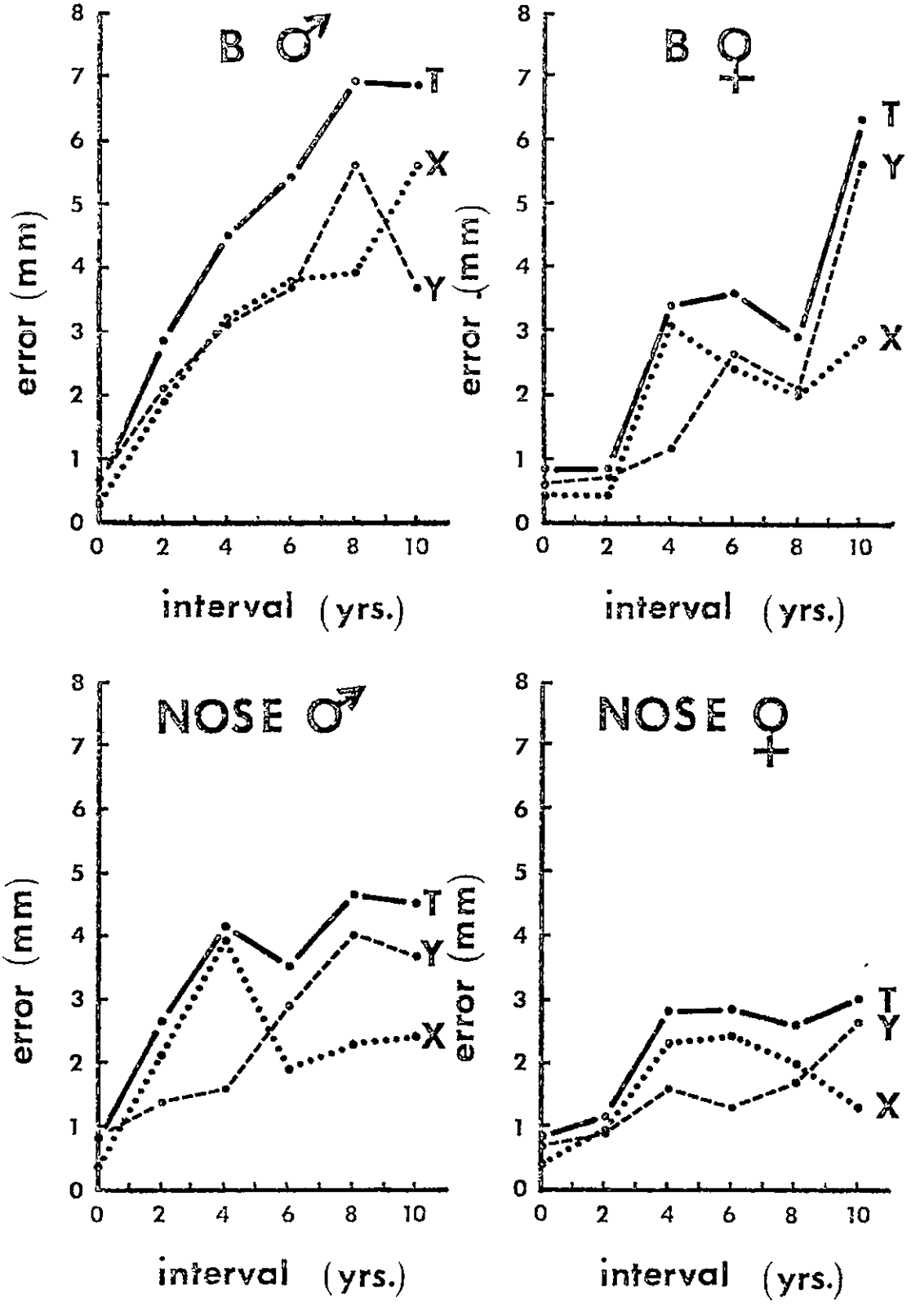

B ♂
B ♀
NOSE ♂
NOSE ♀
error (mm)
interval (yrs.)
T
X
Y
0
1
2
3
4
5
6
7
8
0
2
4
6
8
10

Figure 4 (cont.)

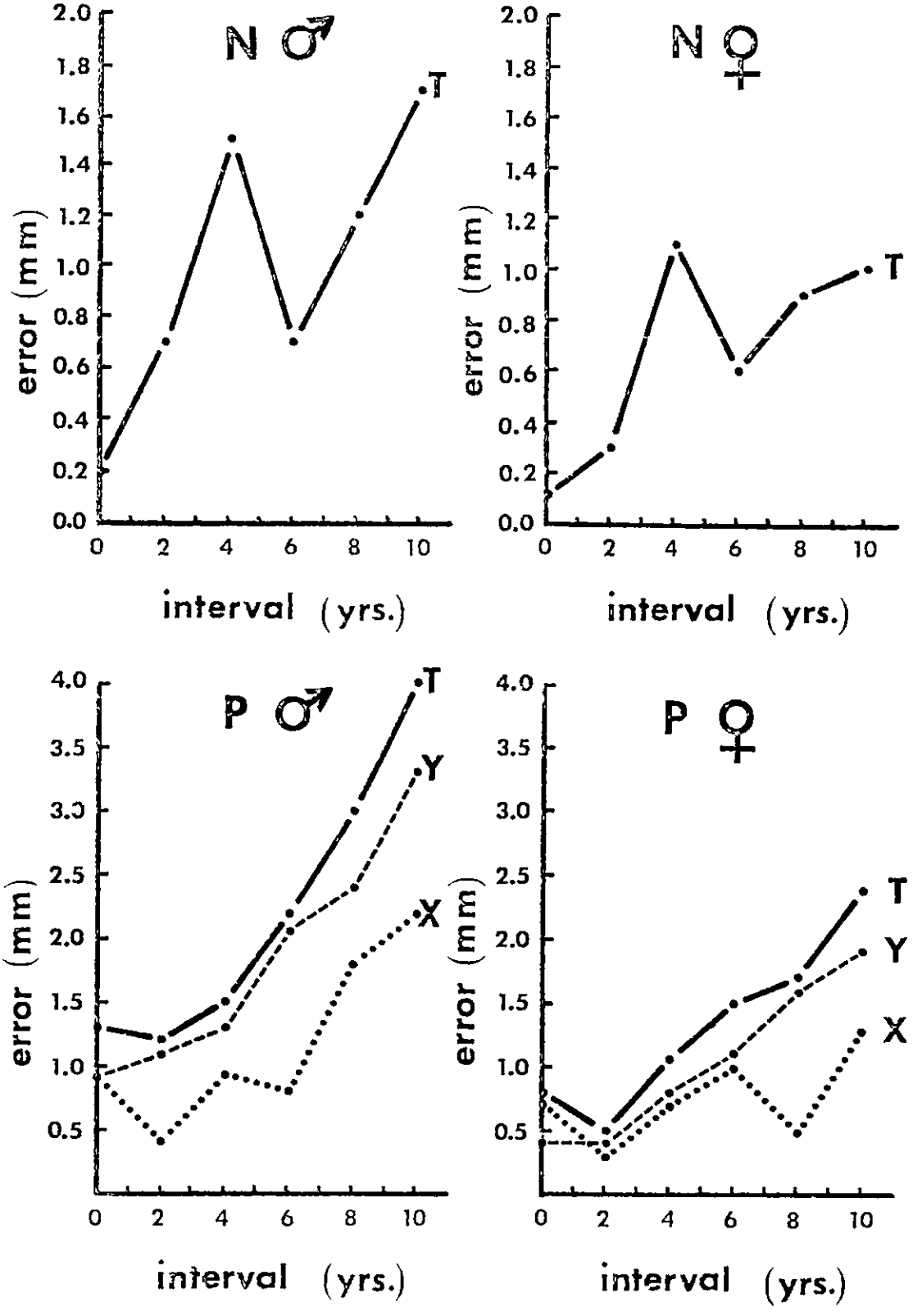

N ♂
N ♀
P ♂
P ♀
T
Y
X
error (mm)
interval (yrs.)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0.5
1.5
2.5
3.0
3.5
4.0
0
2
4
6
8
10

Figure 4 (cont.)

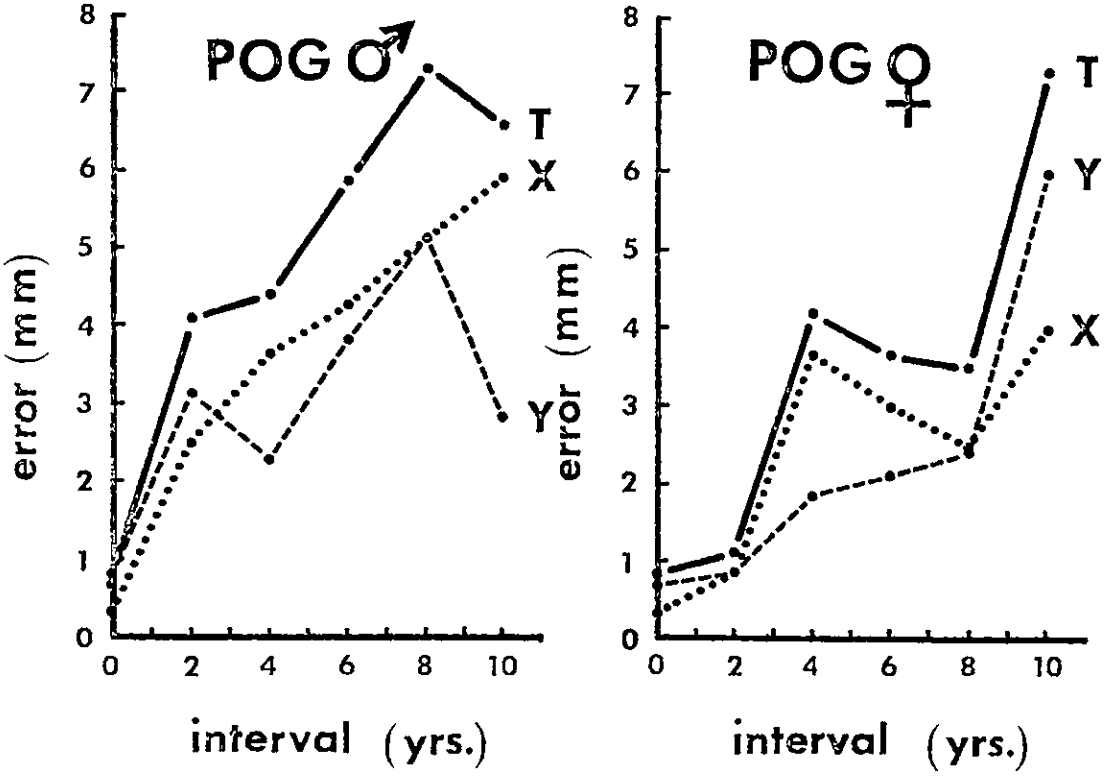

POG ♂
POG ♀
T
X
Y
error (mm)
interval (yrs.)
0
1
2
3
4
5
6
7
8
0
2
4
6
8
10

TABLE VI

TRACING ERROR FOR TWENTY REPLICATIONS
(in millimeters)

Point	Error Component	Males			Females			Males and Females Combined		
		Average Error	Average Absolute Error	Root Mean Squared Error	Average Error	Average Absolute Error	Root Mean Squared Error	Average Error	Average Absolute Error	Root Mean Squared Error
N	X	. .	. .	. .	. .	. .	. .	. .	. .	. .
	Y	. .	. .	. .	. .	. .	. .	. .	. .	. .
	T	0.1	0.1	0.2	0.4	0.4	0.1	0.5	0.1	0.2
P	X	0.2	0.6	0.9	0.0	0.5	0.7	0.1	0.5	0.8
	Y	0.2	0.6	0.9	0.1	0.3	0.4	0.1	0.4	0.7
	T	0.3	1.0	1.3	0.1	0.7	0.8	0.1	0.8	1.1
M	X	-0.1	0.4	0.5	0.1	0.3	0.4	0.0	0.4	0.5
	Y	-0.1	0.5	0.7	-0.2	0.6	0.7	-0.2	0.5	0.7
	T	0.1	0.7	0.8	0.3	0.7	0.8	0.2	0.7	0.8
A	X	-0.1	0.2	0.4	0.1	0.2	0.3	0.0	0.2	0.3
	Y	0.0	0.5	0.6	0.0	0.6	0.6	0.0	0.6	0.6
	T	0.1	0.6	0.7	0.1	0.6	0.7	0.0	0.6	0.7
B	X	0.1	0.1	0.3	1.0	0.4	0.4	0.1	0.3	0.4
	Y	-0.4	0.5	0.7	0.6	0.5	0.6	-0.2	0.5	0.7
	T	0.4	0.6	0.7	1.1	0.7	0.8	0.2	0.6	0.8
NOSE	X	0.0	0.2	0.3	0.1	0.3	0.4	0.1	0.2	0.3
	Y	-0.2	0.6	0.8	0.1	0.5	0.7	0.0	0.6	0.7
	T	0.2	0.7	0.8	0.2	0.6	0.8	0.1	0.7	0.8
POG	X	0.1	0.2	0.3	0.2	0.3	0.3	0.1	0.2	0.3
	Y	0.0	0.6	0.7	0.0	0.6	0.7	0.0	0.6	0.7
	T	0.1	0.7	0.8	0.2	0.7	0.8	0.1	0.7	0.8

DISCUSSION

The purpose of a prediction is to predetermine some future event, the outcome of which is uncertain. With respect to cephalometric forecasts, the unknown event is the change in the size or shape of the face. From a scientific viewpoint, any technique which claims to be able to forecast such changes needs to be validated. that is, it needs to be tested on a sample different from the one used to generate it. The purpose of this study was to validate the Johnston Forecast Grid on a sample of one hundred subjects from the files of the Bolton Study. Prediction accuracy was expressed in terms of root mean squared error, average error, and average absolute error.

Root Mean Squared Error

An examination of Table III and Figure 4 reveals three obvious trends:

1. The root mean squared error generally increases as the prediction span lengthens. Thus, it may be said that prediction errors are directly related in magnitude to increase in time span and amount of facial growth encountered;

2. For comparable measurements over similar time intervals, the root mean squared errors for females were generally smaller than those for males;

3. The grid is most accurate for two-year predictions, and for males its accuracy is often greater for six years of prediction than for four, eight or ten years of prediction.

The tendency for error to increase with time is easily explained. With more growth, there is greater opportunity for form to vary and, thus, produce a larger deviation from the mean (or, in other words, larger error). With little growth, little opportunity to vary exists, and errors will be small. Growth predictions can err in two respects--direction and increment. If either or both of these are predicted wrongly, their culumative effect will be magnified over greater time intervals.

The greater accuracy of grid predictions for girls is explained simply by the fact that girls generally demonstrate less total growth than do boys and, as a result, involve fewer grid-intervals. Shorter predictions tend to yield smaller errors.

The apparent relative increase in accuracy for six-year male predictions as compared with four-, eight-, and ten-year predictions cannot be explained solely by consideration of root mean squared errors. Clearly, a bias in the six-year prediction subsamples cannot explain this phenomenon, for all subsamples are distributed quite uniformly on the basis of Angle molar classification (see Table I). An inspection of Table IV (average error) indicates a fairly consistent trend for horizontal (X) and vertical (Y) error to change from negative to positive, or from more negative to less negative with increasing years of prediction. This would probably indicate that the individualization for males needs to be altered slightly. Less growth for the ten- and eight-year spans (I would suggest a decrement of 0.5 growth units for both spans) and additional

growth for the four-year span (an additional 0.5 increment) may help improve the grid's accuracy for individualized male predictions (Figure 5); however, a future study would be necessary to validate these proposed changes. It should be stated clearly that the individualization employed here never alters growth directions, but, rather, attempts to tailor the addition of grid-units to reflect the fact that the individual can be assigned to a distinct, less variable subpopulation on the basis of age, sex, and prediction-interval. Accordingly, a modification of direction as well as increment also might serve to reduce overall error. It may be noted here that simplicity of the grid allows modifications such as the ones proposed to be effected quite readily and their implications to be easily understood by the specialty.

In theory, the same flexibility should be available to the RMDS approach; however, the computer hardware and programs employed by RMDS are quite technical and are not readily understood by the average user of this service. Hence, it is difficult to evaluate the service at any given point in time. However, it does not seem unreasonable that non-technical explanations of the software and the theoretical bases for occasional modifications could be made available to interested professionals, with more technical information being provided for the less diffident student of the predictive arts.

Computer Individualization

Schulhof and Bagha (1975) have reported that computerized

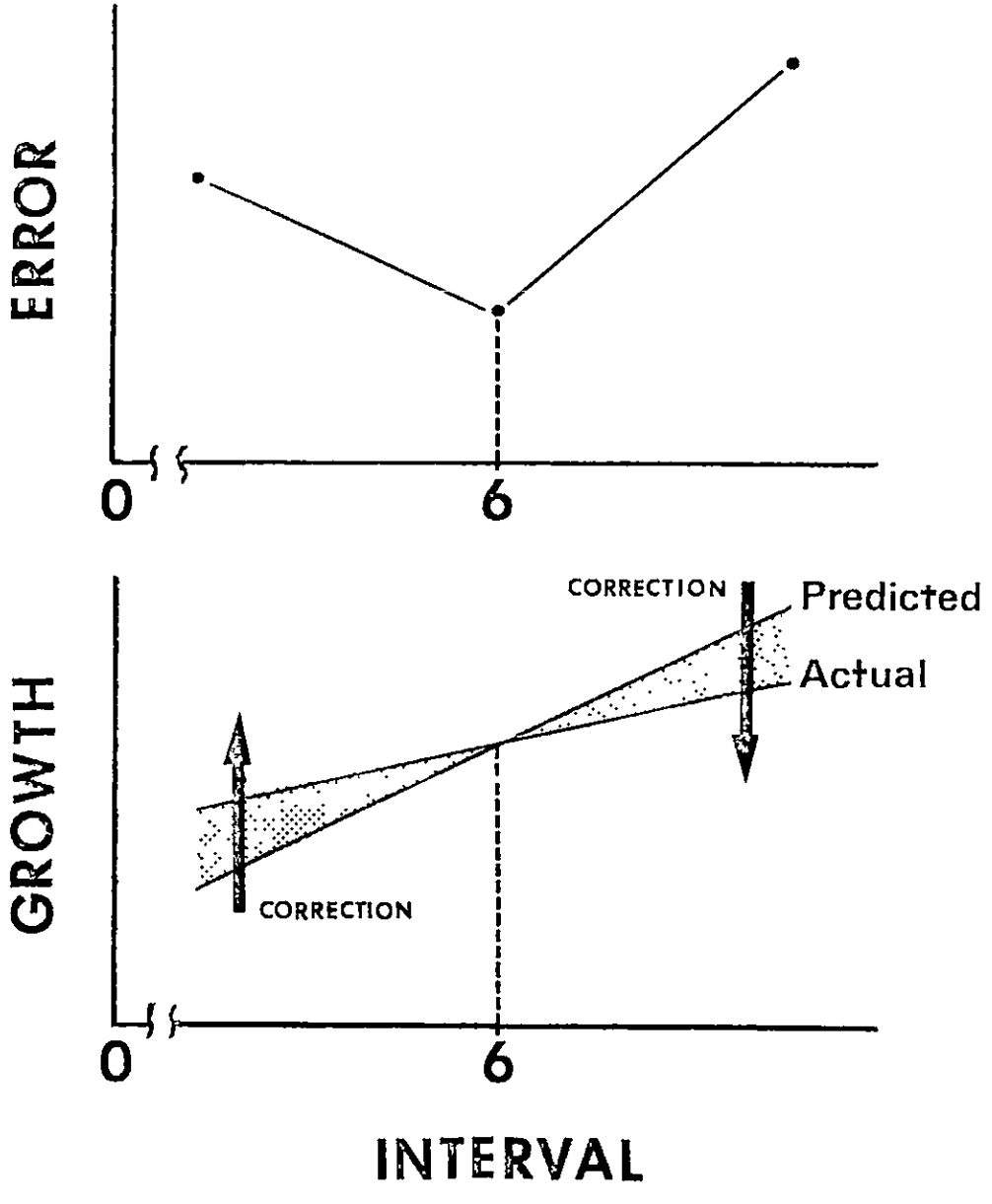


Figure 5.--Origin of prediction errors for males and proposed correction.

predictions are more efficient for extreme patterns of growth. Although these represent a relatively small percentage of an average practice, they often constitute a considerable proportion of the so-called "problem cases." Inasmuch as Schulhof and Bagha have not characterized the nature of the independent variables used, a complete discussion of the technique would be a welcome addition to the literature. However, to test the claim that computer prediction is superior to the other schemes in spotting unusual growth patterns and compensating for them, a fairly simple procedure was employed. Original tracings (at ten years), five-year arcial predictions without treatment, and final tracings (at fifteen years) executed by RMDS for twenty Bolton Study subjects as part of another study (Greenberg, 1972), were obtained and the predicted and actual change in the horizontal position of pogonion measured. The changes in both categories (predicted and actual) were ranked ordinally, each category being divided equally into "high" and "low" sub-categories and Fisher's test of exact probabilities employed to examine whether the size of the prediction was related to the size of the change (i.e., that predictions will be suitably small for small actual changes, and large for large changes). Although there was a slight tendency for large changes to be associated with large predictions, the result was not statistically significant ($P = .08$).

RMDS vs Grid

A discussion of the accuracy of the Johnston Grid takes on added meaning in comparison to the Ricketts synthesis. A comparison

was effected by using the sample of twenty RMDS five-year predictions and tracings used in Greenberg's 1972 study (vide supra). Grid predictions were performed on the initial tracing, and, using a sella-nasion superimposition (registered at sella), the computer-predicted points, as well as the actual outcome, were added to the forecast. The distances between the computer-predicted location and the grid-predicted location (computer vs grid), the computer location and the actual location (computer vs actual), and the grid location and actual location (grid vs actual) were measured and recorded for each landmark. Mean errors and root mean squared errors were calculated and tabulated (Table VII). The variances of computer vs actual and grid vs actual were contrasted using F-ratios. Based on this sample, no statistically significant difference in predictive accuracy could be inferred for the two schemes. Although both the root mean squared error and the mean error for the Ricketts method were smaller than that of the grid for four of the seven landmarks, the overall result could hardly have been closer.

Comparison of Published Values

Johnston, Schulhof and Bagha, and the present author have all calculated root mean squared errors for one or more of the contemporary schemes. It was felt that a comparison of these data, where possible, would prove interesting. The data for the various studies were not exactly comparable in their original form, necessitating the computation of averages in some instances. The values published by Schulhof and Bagha (1975) were not separated for males and females, whereas

TABLE VII

ERROR ANALYSIS COMPARING TWENTY COMPUTER AND TWENTY GRID PREDICTIONS TO EACH OTHER, AND TO ACTUAL OUTCOME

(in millimeters)

Grid Point	Comparison	Mean Error	Root Mean Squared Error
N	Computer vs Grid	1.1	1.4
	Computer vs Actual	1.1	1.5
	Grid vs Actual	1.8	2.0
P	Computer vs Grid	2.0	2.1
	Computer vs Actual	2.2	2.5
	Grid vs Actual	2.4	2.8
M	Computer vs Grid	1.6	2.0
	Computer vs Actual	2.1	2.6
	Grid vs Actual	2.2	2.7
A	Computer vs Grid	1.6	1.9
	Computer vs Actual	3.0	3.3
	Grid vs Actual	2.9	3.2
B	Computer vs Grid	2.0	2.5
	Computer vs Actual	4.4	4.9
	Grid vs Actual	4.6	5.1
NOSE	Computer vs Grid	2.7	3.1
	Computer vs Actual	5.3	4.7
	Grid vs Actual	4.7	3.9
POG	Computer vs Grid	3.2	3.8
	Computer vs Actual	5.1	5.7
	Grid vs Actual	4.9	5.4

the data of Johnston (1975) and the present study were separated by sex. Therefore, males and females were averaged to make them comparable. In Johnston's paper the predictions were made for a five-year interval, whereas Schulhof and Bagha examined a mean prediction-interval of 9.42 years. The intervals in this study were different from either of the other two, but the ten-year interval used here is felt to be roughly comparable to 9.42 years, placing the ten-year grid prediction at, if any, a slight theoretical disadvantage in comparison to Schulhof and Bagha's results. Values for a five-year interval were estimated from the present study by averaging the combined male and female data for four- and six-year intervals. All the values obtained in this manner are shown in Table VIII. Several similarities and contrasts are apparent:

1. Values obtained in this study for five-year grid predictions are quite similar to Johnston's values.

2. Values obtained in this study for five-year RMDS predictions are similar to 9.42 year RMDS prediction values obtained by Schulhof and Bagha.

3. Errors for only three landmarks of seven used in the grid method were evaluated by Schulhof and Bagha. Their values for pogonoin agrees quite closely with information obtained in this study, but the values for A-point and nose obtained by Schulhof and Bagha were larger (63% and 53%, respectively) than for the present study.

The observed similarities are not particularly remarkable when one considers that the three schemes are basically quite similar. However, the contrasts are noteworthy. The values obtained by

TABLE VIII

COMPARISON OF ROOT MEAN SQUARED ERROR
BY INVESTIGATOR AND SCHEME
OF PREDICTION
(in millimeters)

Point	Error Component	Investigator					
		Schulhof and Bagha[a]		Author[c]			Johnston 1975
		Grid	RMDS	Grid 10 Yrs.	Grid 5 Yrs.	RMDS 5 Yrs.	Grid 5 Yrs.
N	T	. .	. .	1.4	1.0	1.5	1.0
M[b]	X	. .	. .	3.9	1.9	. .	2.2
	Y	. .	. .	2.8	2.1	. .	2.3
	T	. .	3.4	5.3	2.9	2.6	3.7
A	X	. .	. .	2.5	1.7	. .	1.9
	Y	. .	. .	2.1	1.3	. .	2.3
	T	5.2	3.2	3.4	2.2	3.3	3.0
B	X	. .	. .	4.2	3.1	. .	3.3
	Y	. .	. .	4.7	2.7	. .	1.6
	T	. .	. .	6.6	4.2	4.9	3.7
NOSE	X	. .	. .	1.9	2.6	. .	. .
	Y	. .	. .	3.2	1.9	. .	. .
	T	6.2	5.6	3.8	3.3	4.7	. .
POG	X	. .	. .	5.0	3.7	. .	. .
	Y	. .	. .	4.4	2.5	. .	. .
	T	7.5	4.8	7.0	4.5	5.7	. .
P	X	. .	. .	1.8	0.9	. .	1.2
	Y	. .	. .	2.6	1.3	. .	1.3
	T	. .	. .	3.2	1.6	2.5	1.7

[a]Mean prediction span, 9.42 years; [b]Grid predicts upper first permanent molar position; computer predicts lower first permanent molar; [c]Males and females, combined.

Johnston and by the author for A-point and nose are clearly in disagreement with Schulhof and Bagha's findings. It may be hypothesized that a small part of the disparity is due to the lack of individualization in their grid forecasts (the individualization table was not prepared at the time of their study). However, barring the (highly unlikely) possibility that they incorrectly used the grid, no reasonable explanation, other than sampling variation, can be advanced. With regard to pogonion, the accuracy of computer and grid forecasts are comparable at five-year intervals, but the RMDS method seems more accurate for this point at the ten-year interval.

Technical Error

Technical error is a major problem in the cephalometric technique, and one which can be minimized but never completely eliminated.

The largest percentage of technical error in the Ricketts computerized scheme is related to the steps executed by the cephalometric technician who must trace the initial cephalogram, locate the points (many of which seem to be unreliable and imprecisely defined) to be digitized, and retrace the anatomy by regional superimposition on the computer relocated landmarks. Although it is probable that RMDS technicians are highly skilled and well-trained, the reduction in error achieved by the use of sophisticated technology to relocate and plot the points is probably offset by the additional steps required to execute the finished forecast.

Moreover, tracing and measurement error is not the only possible source of error in the cephalometric technique. Error in orienting the patient in the cephalostat and radiographic enlargement are other factors.

In view of the errors seen here (whatever their source) the future of improved short-range cephalometric prediction would seem to depend heavily upon reducing technical error until it becomes an insignificant part of the changes to be forecast. The possibilities here are not promising. Improvement in long-range forecasts would undoubtedly require a major advance in our knowledge of craniofacial growth. We need to pass from an era of describing facial growth to one of comprehending underlying biological processes.

SUMMARY AND CONCLUSIONS

Although cephalometric growth prediction is highly controversial within the orthodontic specialty, a computerized commercial prediction service has been made available by Rocky Mountain Data Systems, Inc. Recently, an additional method--the so-called Johnston Forecast Grid--has been developed. Although it is claimed that the grid produces forecasts of accuracy comparable to that of more complex methods, published validations are fragmentary and somewhat contradictory.

Accordingly, an independent validation of the grid method was undertaken on a sample of 100 subjects for intervals ranging from two to ten years. In addition, its accuracy was compared to an additional sample of 20 five-year forecasts generated by the commercial service.

Average errors, average absolute errors, and root mean squared errors were calculated for both the grid and computerized forecasts.

The following conclusions were drawn:

(1) The accuracy of grid forecasts decreased in direct proportion to the prediction-interval.

(2) The accuracy of the grid-forecasts were almost identical to that of predictions generated commercially.

(3) Estimates of accuracy reported here are, in certain respects, different from those published for smaller samples.

(4) Reduction in technical error would be necessary to

effect a marked improvement in the accuracy of short-term forecasts.

(5) Improved accuracy for long-range forecasts will require a genuine breakthrough in our understanding of the mechanisms of craniofacial growth.

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APPENDIX

FILE NUMBERS OF ONE HUNDRED CASES FROM THE BOLTON-BRUSH GROWTH STUDY USED IN THE PRESENT STUDY LISTED BY SEX, INITIAL AND FINAL AGES

Males

8-18 Yrs.	10-18 Yrs.	12-18 Yrs.	14-18 Yrs.	16-18 Yrs.
1. B2686	1. B2049	1. B2426	1. B3422	1. B3225
2. B2274	2. B3256	2. B3302	2. B3130	2. B442
3. B113	3. B2446	3. B2733	3. B3262	3. B153
4. B2216	4. B2202	4. B3204	4. B3706	4. B2414
5. B1892	5. B2668	5. B2816	5. B3168	5. B945
6. B259	6. B2102	6. B2478	6. B3537	6. B403
7. B2285	7. B2094	7. B3219	7. B1024	7. B1192
8. B2656	8. B3471	8. B3477	8. B2990	8. B3424
9. B2531	9. B3356	9. B3483	9. B1532	9. B2494
10. B3149	10. B1681	10. B3007	10. B1157	10. B4141

Females

6-16 Yrs.	8-16 Yrs.	10-16 Yrs.	12-16 Yrs.	14-16 Yrs.
1. B3047	1. B2436	1. B2903	1. B4400	1. B3484
2. B2491	2. B2457	2. B3066	2. B3526	2. B3488
3. B1894	3. B2425	3. B3177	3. B3213	3. B3503
4. B2220	4. B112	4. B3197	4. B3714	4. B3505
5. B2357	5. B1916	5. B3285	5. B3557	5. B3517
6. B1917	6. B1883	6. B1108	6. B3254	6. B3546
7. B2243	7. B2146	7. B2398	7. B3289	7. B3362
8. B2203	8. B2409	8. B2382	8. B3315	8. B3244
9. B2615	9. B2440	9. B3355	9. B3312	9. B3223
10. B2871	10. B2480	10. B3433	10. B2336	10. B3367