Original Article

Electronic cephalometric diagnosis: Contextualized cephalometric variables

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Abstract

Introduction: Classical parametric assessments and isolated cephalometric variables may not provide the best information in craniofacial morphology. Rather, contextualized cephalometrics can be more promising, since it allows for integration among weighty cephalometric variables. **Objective:** The main purpose of this manuscript is to present the application of a non-trivial mathematical model in cephalometrics, providing data mining by filtering certainty and contradiction in each network "node". **Methods:** In the proposed "neural network", each "cell" is connected to others "cells" by "synapses". Such decision-making system is an artificial intelligence tool tailored to potentially increase the meaning of assessed data. **Results:** The comparison between the final diagnosis provided by the paraconsistent neural network with the opinions of three examiners was heterogeneous. Kappa agreement was fair for anteroposterior discrepancies, substantial or fair for vertical discrepancies and moderate for dental discrepancies. For the bimaxillary dental protrusion, the agreement was almost perfect. Similarly, the agreement among the three examiners, without any software aid, was just moderate for skeletal and dental discrepancies. An exception was dental protrusion, which agreement was almost perfect. **Conclusions:** In conclusion, the analysis of performance of the developed technology supports that the presented electronic tool might match human decisions in the most of the events. As an expected limitation, such mathematical-computational tool was less effective for skeletal discrepancies than for dental discrepancies.

Keywords: Cephalometric diagnosis. Non-trivial logics. Artificial intelligence.

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INTRODUCTION

In orthodontics, as in any other medical or dental specialty, it is possible to apply mathematical parameters to biological systems. Before the premises are set, the evidences may be considered as coincidences or as "truth", although "truth" may hold significant uncertainty or contradiction.

Routinely, cephalometric data have been extensively described in the orthodontic literature. With no doubt, the most of such data is expressed by means and standard deviations. Central tendency measurements are frequently criticized because they present just a general view of a specific problem, far less than the desired individualized information.

Therefore, with clear limitation, means and standard deviations force the orthodontist to allocate each variable in certain pre-determined classes, many times academically well accepted, however, not always biologically proofed. The values can be interpreted with a "flexible" allocation, allowing that a value refers to two sequential classes, with certain degree of pertinence to each one of them. In this case, the application of mathematical values to the understanding of natural phenomena is probably better.

With such support, the theory of the fuzzy logic[1,2] was presented. According to such theory, values are pertinent to more than a pre-determined class, what means that a specific value may refer to two sequential classes, with certain degree of pertinence to each one. The fuzzy logic was applied in orthodontics to select types of headgears[3], to evaluate the visual subjective judgment of the anteroposterior relationship between maxilla and mandible[4,5] and to establish non-surgical treatment plans.[6] However, a mathematical model based upon fuzzy and paraconsistent logic in order to contextualized cephalometric data has not been presented.

In general, cephalometric is limited because cephalometric variables hold important degrees of imprecision when individually analyzed. Without the "whole picture", there is no clear "*gestalt*" about the craniofacial architecture of each person, what means that there is no trustable screening of a possible discrepancy and its degree of severity. Such limitations make the clinical application of cephalometry less effective than what is expected by clinical orthodontists.

A better scenario would be to setup specific software that could quantify how much "noise" is carried by each cephalometric variable, weighing its relative contribution to a general index of discrepancy. Such approach would offer a significant progress in regard to the current cephalometric comparisons, which are simple measurements of central tendency, as means and standard deviations.

Furthermore, the application of paraconsistent logic[7-10] allows the mathematical modeling of imprecise and inconsistent data. Therefore, it is possible to detect and control contradictions, targeting to provide more and better answers to old problems. In this study, the paraconsistent logic was applied to contextualize selected cephalometric variables, throughout neural networks, which considered the degrees of certainty and contradiction in each one of its "cells".

PROPOSITION

The goals of this project are:

1. To present a mathematical-computational model to process interactions among cephalometric values.
2. To validate the performance of such artificial intelligence tool, comparing to the opinions of three specialists in orthodontics, even not having a golden standard for such approach.
3. To classify in a ranking the degree of agreement between the opinion of the examiners and the electronic cephalometric diagnosis, in specific parts or dimension of the craniofacial complex.

MATERIAL AND METHODS

The following cephalometric landmarks (Fig 1) were selected:

1. Basion (Ba): the most inferior posterior point on the posterior margin of the foramen magnum.
2. Sella (S): the center of the pituitary fossa of the sphenoid bone.
3. Nasion (N): the junction of the frontal and nasal bones, at the fronto-nasal suture.
4. Pterygo-maxillary fissure (PtgI): the most inferior point of the pterygo-maxillary fissure.
5. Posterior nasal spine (PNS): the most posterior point on the bony hard palate.
6. Anterior nasal spine (ANS): the tip of the median anterior bony process of the maxilla.
7. Upper molar: the most inferior point of the mesial cuspid tip of the first upper molar, posterior reference for the occlusal plane.
8. Anterior reference of the occlusal plane: established by bisecting the overbite or openbite of the incisors, considering the incisal edges of the upper and lower incisors.
9. Gonion (Go): the most postero-inferior point of the angle of the mandible.
10. Menton (Me): the most inferior point on the mandibular symphysis.
11. Gnathion (Gn): the most anterior and inferior point on the contour of the symphysis. Determined by bisecting the angle formed by the mandibular plane (Go-Me) and the Nasion-Pogonion line.
12. A Point: the most posterior point on the anterior curvature of the maxilla.
13. B Point: the most posterior point on the anterior curvature of the mandibular symphysis.
14. Pogonion (Pg): the most anterior point on the contour of the bony chin.
15. Upper incisor edge: the incisal tip of the maxillary central incisor.
16. Upper incisor apex: the root tip of the maxillary central incisor.
17. Lower incisor edge: the incisal tip of the mandibular central incisor.
18. Lower incisor apex: the root tip of the mandibular central incisor.

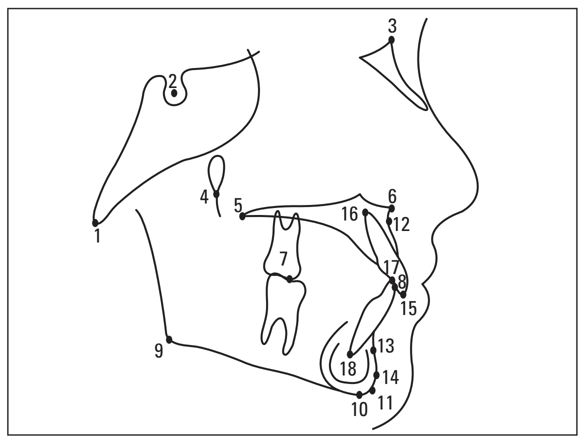

FIGURE 1 - Selected cephalometric variables.

1. Anterior Cranial Base
2. Palatal Plane (PP)
3. Occlusal Plane (OP)
4. Mandibular Plane (MP)
5. Cranial Base
6. Y Axis
7. Posterior Facial Height
8. Anterior Facial Height – Middle Third
9. Anterior Facial Height – Lower Third
10. Anterior Facial Height
11. SNA
12. SNB
13. Long Axis – Upper Incisors
14. Long Axis – Lower Incisors
15. A Point – Pogonion Line

Wits: distance between the projections of A Point and B Point on the occlusal plane

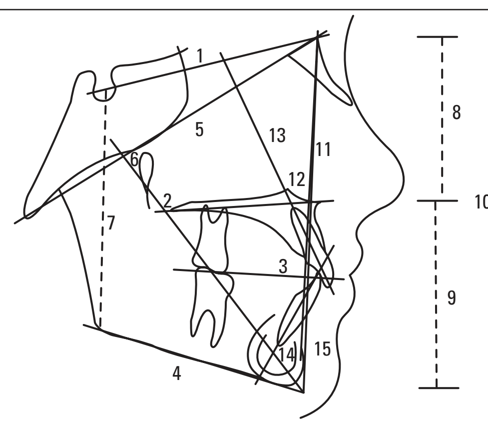

FIGURE 2 - Cephalometric analysis.

The means and standard deviations of the described cephalometric measurements (Fig 2) were provided by a Brazilian cephalometric atlas.[11] The values were allocated by age and gender and the means and standard deviation were z-scored, before the mathematical modeling.

The selected cephalometric variables were divided in three units:

» Unit I: related to the anteroposterior discrepancy. Variables: divided into two levels of information (level 1 prioritized to level 2). The level 1 included the variables ANB and Wits. In the level 2, there was a composition of the results of level 1 with the variables SNA and SNB.

» Unit II: related to the vertical skeletal discrepancy.[12] Variables: 1) S-Go/N-Me Proportion; 3) Y Axis angle and; 3) SN/PP, SN/OP and SN/MP angles.

» Unit III: related to the dental discrepancies. Variables: divided into three different levels (without priority): 1) Upper incisors: U1.PP angle, U1.SN angle and the linear measurement U1-NA, taking in account the SNA angle (from Unit I); 2) Lower incisors: L1.APg angle, L1.NB angle, L1.GoMe angle and the linear measurements L1-APg and L1-NB, taking in account the SNB angle (from the unit 1); 3) Relationship between the upper and lower incisors: U1.L1 angle.

LIMITATIONS OF THE CONVENTIONAL CEPHALOMETRIC ASSESSMENT

Considering that the average of the ANB angle for a young adult (18 year-old male) is 2° (Skeletal Class I) and the orthodontist wants to evaluate the anteroposterior relationship using such cephalometric reference, even assuming that significant limitation is involved, let us describe such conventional cephalometric diagnostic process.

It is well known that the use of cephalometric variables assumes landmark location, tracing reproducibility, clinical significance errors and others. To exemplify some of them, in such particular case, the ANB value may incorporate errors such as the position of the Nasion (due to the length and/or inclination of the anterior cranial base), the limited identification of A point and the vertical facial features of the assessed patient. Observe that such errors may be due to the limitations of the cephalometric method or due to the geometrical camouflage. Geometrical camouflage is, for instance, the ANB angle be smaller than the actual discrepancy because of a long or steep anterior cranial base.

Independent of the nature of the limitation, methodological or geometrical, the possible use of the ANB angle takes to the next question: "In this specific case, which value for the ANB angle

μ = Certainty axis, i.e., favorable evidence.
- Positive values indicate the degree of trueness.
- Negative values indicate the degree of falseness.

λ = Contradiction axis, i.e., unfavorable evidence.
- Positive values indicate the degree of inconsistency.
- Negative values indicate the degree of ignorance.

Extreme States:
T = +1; Absolutely True
F = -1; Absolutely False
⊤ = +1; Absolutely Inconsistent
⊥ = -1; Absolutely Unknown

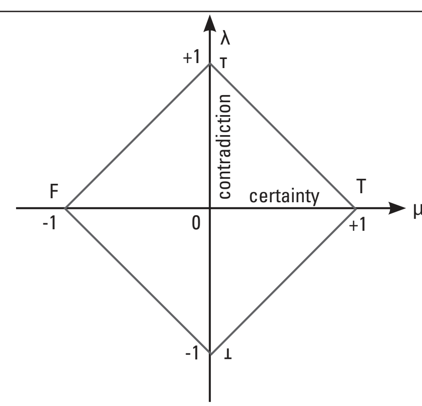

FIGURE 3 - Description and graphic illustration of the "basal cell" of the paraconsistent logics.

would be coherent with an actual scenario of skeletal Class II or Class III?" In the most of the cases, the answer is not clear. Other cephalometric information as Wits, SNA, SNB (and many others) could be elected to help to answer such question.

NEURAL NETWORK AND PARACONSISTENT LOGIC

The model of "artificial intelligence" applied in the current project, targeting to enhance the meaning of conventional cephalometric data, makes decisions in each one of the "nodes" of the proposed neural network, filtering degrees of certainty and contradiction. As a result, in each assessed case, degrees of evidence of abnormality quantify the favorable and unfavorable evidences for each attribute of interest, for each region or dimension considered by the program.

CONTEXTUALIZING CEPHALOMETRIC VARIABLES

The statement can be formulated under a different view: "In this case, how high or low/negative is necessary for the value of ANB to allow certainty that it is a skeletal Class II (or Class III)?" Such quantification is represented by the axis [μ] (Certainty Axis, Fig 3). An extremely high ANB value, which clearly indicates a skeletal Class II, could be, for instance, 10° (Fig 4). It can be affirmed that, if ANB is equal or higher than 10°,

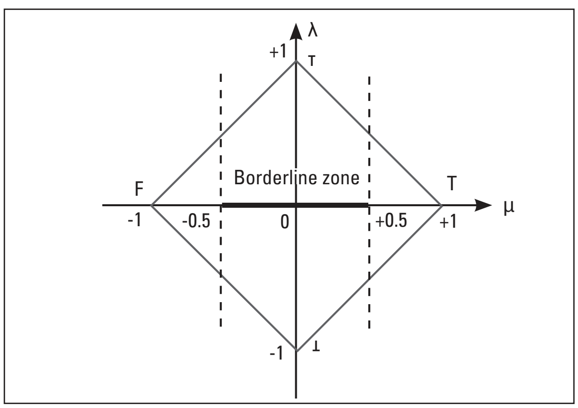

FIGURE 4 - Borderline zone.

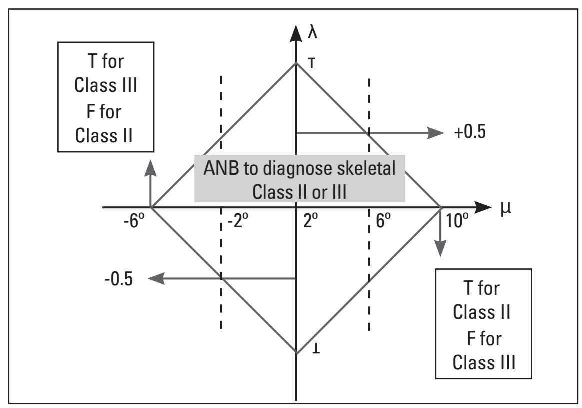

FIGURE 5 - Examples of ANB angles.

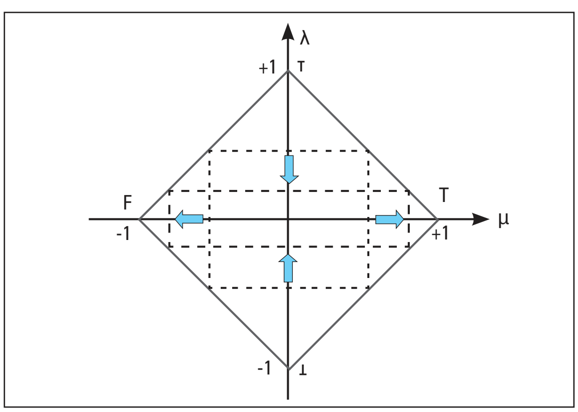

FIGURE 6 - The [μ] values distant from the norm correspond to the decrease of the [λ] values.

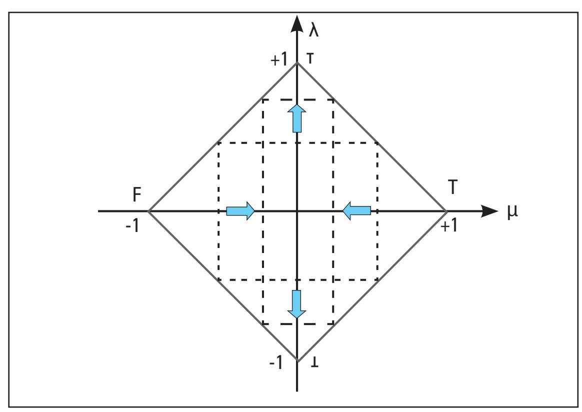

FIGURE 7 - The [μ] values near to the norm correspond to the increase of the [λ] values.

T = +1 and the individual clearly presents a skeletal Class II. In the same manner, an extremely low value for skeletal Class III could be, for instance, -6° (Fig 5). If ANB is equal to or lower (negative) than -6°, F=-1, and the individual clearly does not present a skeletal Class II. Degrees of trueness (T) and falseness (F) are represented with a "mirror image" (Fig 5) in order to show the possibility of the discrepancy to be a scenario of skeletal Class II or skeletal Class III.

The intermediary values, in between the extreme states already mentioned, are located in the borderline zone $0.5 \leq \mu \leq 0.5$ (Fig 4); that means that the graphic shows ANB values, that in this case, cannot guarantee trueness or falseness of the occurrence of events like skeletal Class II or Class III.

Over the [μ] axis, as far as the ANB value is distant from the norm, the degree of contradiction showed in the [λ] decreases, for skeletal Class II or III, since such ANB angle reflects with lesser uncertainty a skeletal discrepancy (see arrows, Fig 6).

When the ANB angle is close to the norm (or is the norm), the scenario of a skeletal discrepancy only occurs if the information "ANB angle" is significantly inconsistent or unknown (see arrows, Fig 7). If [λ] is the extreme value $\top = +1$, means that is absolutely inconsistent with the scenario of a skeletal Class II or Class III and if [λ] is the extreme value $\bot = -1$, means that the value is absolutely unknown to identify such scenario.

SAMPLE FOR VALIDATION OF THE PROPOSED MODEL

The sample for validation consisted of 120 cephalometric tracings, retrospectively analyzed, of Caucasian individuals which sought for orthodontic treatment in a private office, which radiographs were consecutively selected form the files of the author. Such sample included 53 males and 67 females, from 06 to 53 year-old. Twenty two patients (18.3%) were older than 18 year-old and were considered adults. The inclusion criteria for this specific sample were: 1) To be Caucasian (to match the data of the atlas[11]) and; 2) To have a lateral radiograph taken in the same cephalostat (Lúmina Radiologia, São Paulo, SP, Brazil). The exclusion criteria were: 1) To present any craniofacial deformity or syndrome and; 2) Radiographs with bad quality (head positioning or processing).

DATA COLLECTION

The lateral radiographs were traced by an orthodontist-operator and digitalized by other operator. A 0.03 mm mechanical pencil and orthodontic acetate paper were used for the orthodontic tracing. The tracings were digitalized in the Summasketch III table (Summagraphics Corporation, Scottsdale, AZ, USA) and collected by software developed to operate the cephalometric electronic system (Iris Informática, São Paulo, SP, Brazil).

SYSTEMATIC AND METHOD ERRORS

In order to calculate the systematic and method errors (Dahlberg[13] formula), a sub-sample of 15 radiographs, chose by random selection (one in every five radiographs, starting with the 20^{th} case of the sample) was re-traced and re-digitalized, in a 4 week interval. Taking into consideration both operators, there was no statistically significant systematic error for any assessed cephalometric variable. Taking into consideration both operators again, the method error varied from 0.46 mm (S-Go variable) to 0.94 mm (N-ANS) and from 0.33° (Y axis variable) to 0.94° (SN-OP variable).

MATHEMATICAL-COMPUTATIONAL MODELING

The system was developed considering eighteen cephalometric landmarks, modeled by 223 Boolean inference rules, which resulted in 405 possible categories. The software code-sources for both, mainframe and feeder, are described in approximately 10 thousand lines of Delphi language (Release 8.0, Borland Inc., Austin, TX, USA) and compatible the Oracle platform (Oracle Corp., CA, USA) by the company Iris Informática (São Paulo, SP, Brazil).

EXAMINERS SELECTION

The tracings and cephalometric values were submitted to three examiners, selected according to their academic education and clinical experience. Inclusion criteria: 1) To hold a PhD degree and; 2) To be involved in research projects and a recognized university and also practice clinical orthodontics. The exclusion criteria were: 1) To know the project by contact with the author and; 2) To demonstrate preference or rejection biases for any cephalometric variable or cephalometric analysis.

STATISTICAL TOOLS

The validation sample (120 cases) was submitted to four assessments: three examiners assessments (subjective and qualitative) and electronic cephalometric analysis (objective and quantitative). The data from all the collections (examiners and software) were pooled and computed by the SPSS statistical package (Release 10.0; Chicago, IL, USA).

RESULTS

The developed neural network contextualized cephalometric data throughout its "synapses", connecting the values [μ] and [λ] of the cells.

The performance of the software was assessed by Kappa agreement indexes,[14] which parameters are presented in the Table 1. The opinions of the three examiners (E1, E2, E3) were tested against the performance of the software, besides the indexes of agreement between the examiners without the software (Table 2).

The Kappa index of agreement was fair for anteroposterior discrepancies, substantial or fair for vertical discrepancies and mainly moderate for dental discrepancies. For the bimaxillary protrusion, the agreement was almost perfect. Furthermore, the agreement among the opinions of the three examiners was moderate for skeletal and dental discrepancies and almost perfect for the bimaxillary protrusion.

DISCUSSION

Neural artificial networks can be described as computational systems which allow the connection among "cells". As biological neurons, the "artificial neurons" are united by "synapses", which connections might be "excitatory or inhibitory".

TABLE 1 - Meaning of the Kappa indexes of agreement.[14]

Kappa Index	Meaning
0.00	No agreement
0.00-0.19	Poor agreement (P)
0.20-0.39	Fair agreement (F)
0.40-0.59	Moderate agreement (M)
0.60-0.79	Substantial agreement (S)
0.80-1.00	Almost perfect agreement (AP)

TABLE 2 - Kappa indexes between the examiners and the software, and also among the examiners.

Attribute of Interest	E1 X Software	E2 X Software	E3 X Software	E1 X E2 X E3
Anteroposterior discrepancy	0.34 – (F)	0.29 – (F)	0.37 – (F)	0.49 – (M)
Vertical discrepancy	0.75 – (S)	0.37 – (F)	0.67 – (S)	0.53 – (M)
Upper incisors positioning	0.44 – (M)	0.22 – (F)	0.45 – (M)	0.47 – (M)
Lower incisors positioning	0.45 – (M)	0.08 – (P)	0.46 – (M)	0.42 – (M)
Upper and lower incisors	0.92 – (AP)	0.85 – (AP)	0.89 – (AP)	0.84 – (AP)

The advantage of the use of neural artificial networks in regard to the conventional computational programming is its ability to solve problems that do not have direct algorithm solutions or the solutions are very complex, as the cases of predictions and pattern recognition, and therefore would demand intense computational processing.

The present model of artificial intelligence was formatted to prevent inefficient cycles of data processing, since it makes partial and progressive decisions in which one of its "synapses", simultaneously modeling certainty and contradiction, before providing a final decision. Such strategy increases its capacity of data mining throughout the decision tree.

Sophisticated mathematical models have been developed in various areas of Medicine for drug development,[15] for clinical diagnosis,[16] and for image diagnosis interpretation.[17] In all these situations, the neural networks allows for the recognition of hidden patterns and, as logical and direct consequence, better predictions.

In our model of neural network and paraconsistent logic, in which we visualized the contextualization of cephalometric variables, the "artificial thinking" was presented considerably alike the "human being thinking". It is interesting to highlight the fact that the agreement among the three examiners, in regard to the skeletal and dental discrepancies and without any interference of any electronic diagnosis tool, was just moderate. Such fact exposes an important degree of controversy among subjective opinions, even those given by specialists paired by academic education and clinical experience. In the other hand, in regard to the bimaxillary dental projection, measured by the relationship between the upper and lower incisors, the agreement is almost perfect, indicating that the examiners can well recognize a pattern of dental protrusion or dental retroclination with better homogeneity than to identify skeletal discrepancies or individual dental discrepancies in each one of the jaws, maxilla or mandible.

It is also important to point out that the exclusion criteria for sample selection was not to include an individual that was not Caucasian. If it was the case, its values comparison with the reference atlas[11] would not be correct. The examiners were warned about such bias and they have given their opinion, considering the bimaxillary dental projection case-to-case, for Caucasian individuals. If other ethnicities were also considered, for instance afro-Americans, probably the opinions of the examiners about the bimaxillary dental positioning would not be so homogeneous.

In the daily practice, usually borderline scenarios provoke different opinions among diverse specialists. Therefore, in the case of controversial and subjective opinions, to expect substantial or almost perfect agreement for borderline scenarios would be incoherent. In support of that expectation, our results suggest that the given opinions and the electronic measurement of the software converge in most of the cases.

It is important to highlight that subjective comparisons, as is the case of the opinions given by the examiners, do not hold a golden standard of answer. There is no right or wrong. Therefore, it can be stated that the software is not better or worse than the specialists in orthodontics in order to detect cephalometric discrepancies. The "machine" diagnosed as it were "one other specialist".

Without a defined golden standard, lack of a better agreement might be interpreted in two different ways, equally relevant: 1) there is certain difficulty for the software to contextualize cephalometric variables and electronically diagnose an orthodontic case and/or; 2) there is certain difficulty for the orthodontists to interpret cephalometric information and sum them up in a final cephalometric consensus. There is no way to know if both situations occurred and if one was more relevant than the other. Theoretically, therefore, the comparison is relative or, if conservatively interpreted, immeasurable.

However, in certain aspects, as systematization and time consuming, there is clear advantage in the use of an electronic diagnostic system. Because its processing, which is mathematical-computational, is absolutely constant, standardized and clearly quicker, since it does not depend upon subjective and, up to certain point, random human opinions.

The project had also as proposal to know the ranking of difficulty to diagnose different types of discrepancies, skeletal or dental. This is the ranking: the software was less effective for the anteroposterior relationships than for the vertical and dental discrepancies, as happened with the examiners as well. In the bimaxillary relationships between upper and lower incisors, both the electronic diagnosis, as the opinions of the examiners, were expressively homogeneous.

Another characteristic to be discussed is the nominal allocation. For the anteroposterior discrepancy (unit I), 5 classes were determined. For the vertical discrepancy (Unit II) and dental discrepancy (Unit III), only 3 classes were established. Naturally, in terms of probability, a better agreement is expected as less options are given to the software or to the examiners. Therefore, the ranking must be understood by the reader with such bias: in the study design the probabilities were not matched before the assessment. Realistically, the nominal classes were established according to the usual classification given by clinical orthodontists in each one of the described scenarios.

In sum, in general view, the opinions of the examiners were qualitative and subjective, therefore, up to certain point, non-equalized and vulnerable, besides the fact that they demanded long time to be obtained. On the other hand, the software offered quantitative and objective answers, better equalized and that were obtained significantly faster than the agreement between specialists.

CONCLUSION

A mathematical-computational model was developed in order to extract hidden cephalometric patterns from conventional cephalometric data, throughout the quantification of its imprecision and conflicts. The mathematical modeling refined and contextualized cephalometric values, allowing a sound “electronic thinking”, comparable to the opinions of specialists in orthodontics.

Therefore, our results support that, in general, the “electronic opinions” presented by the software are comparable to the human opinions. As an expected limitation, since for malocclusion the electronic perception could not be better than the human perception, the sensibility of the described electronic tool was, as the human, lower for skeletal discrepancies than for anteroposterior dental projections.

ACKNOWLEDGMENTS

We thank the orthodontists Dr. Selaimen and Dr. Brandão for their opinions as examiners.

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Submitted: October 2008
Revised and accepted: February 2009

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