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Hybrid approach for automatic cephalometric landmark annotation on cone-beam computed tomography volumes

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Introduction: Cone-beam computed tomography (CBCT) is commonly used for 3-dimensional (3D) evaluation and treatment planning of patients in orthodontics, where precision and reproducibility of landmark annotation are required. Manual landmarking is a time- and effort-consuming task regardless of the practitioner's experience. We introduce a hybrid algorithm for automatic cephalometric landmark annotation on CBCT volumes. **Methods:** This algorithm is based on a 2-dimensional holistic search using active shape models in coronal and sagittal related projections followed by a 3D knowledge-based searching algorithm on subvolumes for local landmark adjustment. Eighteen landmarks were located on 24 CBCT head scans from a public dataset. **Results:** A 2.51-mm mean localization error (SD, 1.60 mm) was achieved when comparing automatic annotations with ground truth. **Conclusions:** The proposed hybrid algorithm shows that a fast initial 2-dimensional landmark search can be useful for a more accurate 3D annotation and could save computational time compared with a full-volume analysis. Furthermore, this study shows that full bone structures from CBCT are manageable in a personal computer for 3D modern cephalometry. (Am J Orthod Dentofacial Orthop 2018;154:140-50)

A cephalometric analysis has diagnostic value that depends on the accuracy and reproducibility in identification of cephalometric landmarks on head radiographs or cone-beam computed tomography (CBCT) volumes. Manual cephalometric landmarking and tracing are monotonous, difficult, and time-consuming processes.[1] Many orthodontists choose not to trace cephalograms because of the tedium. For example, a recent study reported that less than 40% of orthodontists perform a cephalometric analysis on pretreatment cephalograms.[1] Specially, experienced orthodontists may believe that there is no need to trace lateral cephalometric radiographs because their judgment may be perceived to be as accurate as a cephalometric analysis.[1] Contrarily, in the same study, over 70% of orthodontists reported using computer-aided digital-tracing software. Therefore, a fast, affordable and automatic 3-dimenional (3D) cephalometric landmarking system for cephalometric analysis can help in diagnosis by avoiding the conventional disadvantages of cephalograms such as overlapped bone structures and facial asymmetries while increasing the impact on orthodontic practice and maintaining diagnostic protocols. CBCT scans have been introduced in orthodontics as a diagnostic tool and are becoming a standard imaging technique,[2] because they provide accurate 3D information about the patient's size and position. We believe that automatic landmark annotation not only could considerably increase a practitioner's efficiency, but also could reduce the associated subjectivity of the annotation, thus saving valuable clinical time.

Recently, several approaches for automatic landmark detection on CBCT volumes have been proposed. From that literature, we describe 4 outstanding contributions. First, Gupta et al[3] proposed an algorithm to locate 20 cephalometric landmarks on 30 CBCT volumes by grouping head-searching sections.

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Table I. Cephalometric landmark definitions[1,2]

Landmark	*Definition*
Sella (S)	Midpoint of rim between anterior clinoid process in median plane
Nasion (N)	Midsagittal point at junction of frontal and nasal bones at nasofrontal suture
Basion (Ba)	Most inferior point on anterior margin of foramen magnum, at base of clivus
Orbitale (O_R and O_L)	Most inferior point on right and left infraorbital rims
Anterior nasal spine (ANS)	Most anterior limit of floor of nose, at tip of ANS
Posterior nasal spine (PNS)	Point along palate immediately inferior to pterygomaxillary fossa
A-point (subspinale)	Most concave point of anterior maxilla
B -point (supramentale)	Most concave point on mandibular symphysis
Gonion (GoR and GoL)	Points in the middle of the curvature on angles of the mandible
Pogonion (Pg)	Most anterior point along curvature of chin
Menton (M)	Most inferior point along curvature of chin
Porion (PoR and PoL)	Most superior point in left and right anatomic external auditory meatus.
Gnathion (Gn)	Perpendicular on mandibular symphysis midway between Pg and M
Incisor inferior (Ii)	Incisal edge of the most prominent mandibular incisor
Incisor superior (Is)	Incisal edge of the most prominent maxillary incisor

Although they reported a 2.01-mm mean localization error, but only 64.67% of the landmarks had accuacy less than 2 mm. Second, Codari et al[4] presented a method for automatic cephalometric landmark location on CBCT volumes. In this approach, after automatic hard tissue segmentation, a nonrigid holistic registration between objective and reference volumes is done. Then, cephalometric landmarks on a reference volume are registered onto the objective volume. They reported a 1.99-mm mean localization error for 21 landmarks on 18 CBCT volumes. Third, Sahidi et al[5] introduced a software for cephalometric landmark localization on CBCT. They reported 14 landmarks localizations with less than a 4-mm mean localization error and 63.57% of landmarks with a mean localization error less than 3 mm using their manual localization (ground truth). Fourth, Makram and Kamel[6] proposed a system for automatic localization of 20 hard tissue cephalometric landmarks using reeb graphs on 3D patient meshes where some nodes were considered as cephalometric landmarks. Ninety percent of their landmarks had a localization error less than 2 mm.

Cephalometric landmarks have been traditionally studied in 2 dimensions in orthodontics. However, because the head is a 3D structure, it is necessary to locate its position in 3D space. In this article, we introduce a hybrid technique based on the active shape models (ASM) of Cootes et al[7] for a holistic automatic 2-dimensional (2D) landmark approximation in related digitally reconstructed radiograph projections. After that, we applied the knowledge-based approach of Gupta et al[2] for landmark localization improvement and adjustment in cropped subvolumes. Our approach has been tested on 24 CBCT volumes for automatic localization of cephalometric landmarks.

Table II. Step-by-step 3D approach to CBCT cephalometric landmarks on hard tissues

Automatic 3D cephalometric landmark annotation		
Start	Loading volume DICOM data	Automated
Step 1	Model-based holistic landmark search	Automated
Step 2	Subvolume cropping	Automated
Step 3	Knowledge-based local landmark search	Automated
End	3D landmark annotation on CBCT volume voxels	Automated

MATERIAL AND METHODS

The sample for this experiment consisted of 24 large field-of-view CBCT head volume scans from the Virtual Skeleton Database[8] from the Medical Image Repository of the Swiss Institute for Computer Assisted Surgery; they are 0.4-mm isometric voxel DICOM volumes with about 320 slices. No demographic data were available, and volumes were not identified by age, sex, or ethnicity. As indicated in Table I18 cephalometric landmarks were selected and manually annotated on sagittal and coronal projections from each volume for ASM training. To establish true positions of selected cephalometric landmarks, manual annotation was independently made twice by 2 observers (R.S.V., J.M.T.) with varying landmarking experience on rendered volumes in 3DSlicer.[9] The mean localization from manual annotation for each landmark was taken as our ground truth.

Our proposed approach for automatic 3D landmarking on CBCT consists of 3 main steps described in Table II and illustrated in Figure 1. DICOM volumes were loaded into MATLAB (MathWorks, Natick, Mass) without previous preprocessing. In the first step, a holistic ASM cephalometric landmark search is performed on corresponding coronal and sagittal digitally reconstructed