Conventional lateral cephalometric radiographs have proven an invaluable part of initial and final records. Orthodontists typically superimpose cephalometric radiographs to evaluate skeletal and dental changes due to growth and orthodontic treatment (Fig. 1). A quality superimposition depends on the accuracy of each cephalometric tracing. Unfortunately, the conventional cephalometric radiographs suffer from a number of inherent flaws. Hatcher outlined and categorized the limitations of two dimensional cephalometric radiographs:

- Patient orientation error: head position
- Hardware orientation error: alignment of imaging device, patient stabilizing device and the image-recording device
- Geometric error: differential magnification created by projection distance
- Association error: difficulty in identifying a point in two or more projections acquired from different points of view

Accordingly, two-dimensional (2D) cephalometric radiographs cannot produce an accurate and reliable image.

Three-dimensional (3D) imaging can overcome many 2D imaging limitations. The introduction of cone beam volumetric imaging (CBVI) has made it possible to overcome the first three limitations listed above. Various proprietary software products, such as OnDemand 3D (CyberMed) and InVivoDental (Anatomage), allow reorienting the 3D volumetric image in a standardized method (Fig. 2). Association remains a source of possible error in CBVI, but recent landmark location and measurements have proven accurate and reliable.

Among the many advantages that CBVI offers, the ability to perform a 3D superimposition is particularly valuable. It is possible to evaluate growth and treatment outcomes in all three dimensions of space. With dental and skeletal change is evident in 3D superimposition, it is easy to evaluate changes in the transverse dimension, which was impossible with conventional 2D cephalograms.

Confronted with dental or skeletal asymmetries, 3D superimposition allows one to evaluate the left and the right side of the dentition or jaws separately. When assessing changes due to orthognathic surgery, 3D superimposition reveals more detailed changes in position of the jaw segments and the condyles.

Although CBVI overcomes many 2D imaging limitations, 3D superimposition will not be any better unless the method of superimposition is accurate and reliable. There are two widely used methods for 2D superimposition—the best fit method and the structural method. In 1983, Björk suggested the structural method in which he showed anterior wall of sella turcica and anterior cranial base, including cribriform plate as stable structures from an early age (Fig. 3). These structures can be reliable references for the overall superimposition. Likewise, the fundamental principles used in a 2D superimposition method can apply to a 3D superimposition. No matter what the method, it is imperative to use stable landmarks as reference structures.

### Approaches to 3D Superimposition

Generally, there are two approaches to 3D superimposition, use of...
registration points or a mathematical algorithm.

**Registration Points:** This approach uses a number of reference points that are registered on two volumetric images. These points are made to coincide when superimposing two images. Dolphin 3D and InVivoDental both use this method, in which several landmarks are picked and registered on the surface of the skull as the reference points (Fig. 4). These registration points are then matched to superimpose two volumetric images from different time points.

After the software initially superimposes the two images, one may fine-tune the superimposition by manually moving the volumes in three planes of space (Fig. 5). This process is time-consuming (a few hours) and largely dependent on operator skill. Errors can occur anytime during landmark visualization, identification or location. It is also challenging to access the anterior cranial base area.
to register any landmarks, since the cranial base is inside the skull. Therefore, for the sake of clear visualization and accessibility, the landmarks such as Nasion on the skull’s external surface are used as registration points. Apparently even an experienced operator can be inaccurate when registering reference points and performing a manual fine-tuning operation.

**Mathematical Algorithm:** The second approach to 3D superimposition uses the mathematical algorithm method, in which a certain volume of interest (VOI) is first defined for use as the reference volume. Then, a particular mathematical algorithm, based on the probability and information theory, calculates the best fit of the two VOIs and automatically superimposes the two volumetric images.

In the probability theory and the information theory, the mutual information of two random variables is a quantity that measures their mutual dependence:

\[
I(X; Y) = \sum_{y \in Y} \sum_{x \in X} p(x, y) \log \left( \frac{p(x, y)}{p(x) p(y)} \right)
\]

Maes proposed a new approach to image registration using a basic concept from the information theory, mutual information (MI), or relative entropy, as a new matching criterion. It uses the statistical dependence or information redundancy between the image intensities of corresponding voxels in both images. Maes achieved subvoxel accuracy completely automatically and without any prior segmentation, feature extraction or other pre-processing steps—making this method very well-
suited for clinical applications.

OnDemand 3D uses this method of superimposition, permitting the operator to select a VOI (Fig. 6). The registered VOI is then used to superimpose the two volumetric images automatically (Fig. 7). It not only surpasses dependency on the operator’s skill to find and register reference structures, but also the automatic process (so-called “fusion”) is much quicker than manual superimposition (a few seconds). Ultimately, this approach truly uses the structural superimposition method of Björk and will be the “gold standard” of 3D superimposition.

In conclusion, with the advent of CBVI and relevant software technology, advancement is on the fast track. 3D superimposition provides a comprehensive, reliable and accurate way of evaluating growth and treatment outcomes.
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