Three-dimensional reconstruction

Part I: Applications and techniques

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Abstract: Three-dimensional reconstruction of cross-sectional imaging data is gaining increasing acceptance by clinicians. Some applications have been introduced in routine imaging. These applications are summarised and discussed. In order to yield a three-dimensional rendered image several steps such as preprocessing, segmentation, interpolation and rendering are necessary and various modifications of each step are possible. The technical possibilities in each step are summarised and described.

Key words: Three-dimensional reconstruction: applications, preprocessing, segmentation, shading, rendering

together with other imaging modalities, was found to be particularly useful in craniofacial dysgenetic malformations and, more generally, for planning of craniofacial surgery. Examples are the different types of craniosynostosis [1] or craniofacial dysostosis [2, 3]. The involvement of the skull base in craniosynostosis can readily be appreciated on a three-dimensional reconstruction thus facilitating planning of surgery.

Another accepted approach is the rendering of fractures within complex anatomical locations such as the skull, cervico-cranial junction, acetabulum and spine [4-7]. This allows a better assessment of the dislocated fragments and the orientation of the fracture lines.

Three-dimensional imaging is also helpful in planning reconstructive joint surgery [8]. It provides better visualisation of the joint structures and can be employed to create and design prosthetic implants and models. Three-dimensional rendering prior to reconstructive surgery has been described, for example, in cases of osteoarthritis, avascular necrosis and fractures of the hip [5].

Three-dimensional display of the brain surface with intracranial electrodes can help to control the exact localisation of epileptic foci in intracranial electroencephalography.

Three-dimensional rendering is useful in radiotherapy. Superimposition of radiation beams over patient anatomy helps treatment planning by the oncologist [9]. Visual estimations and volumetric quantification of the tumour volume enable a more accurate determination of the required radiation dose. Three-dimensional display of nuclear medicine data has also been used [10].

The value of volumetric display and quantification of joint effusion for monitoring treatment is still uncertain. A potential role might arise in the evaluation of inflammatory activity, or in follow-up after treatment with anti-inflammatory drugs. Other applications for three-dimensional reconstruction have been reported, such as rendering of congenital hip dysplasia [11-13], pseudarthrosis after posterior lumbar fusion [14, 15], osteochondritis dissecans of the talus [16], and spinal stenosis due to spondylolisthesis, osteophytes or bone fragments [5].

Introduction

In the future increasing computation speed will considerably facilitate reconstruction of cross-sectional imaging data such as multiplanar reformatting and three-dimensional reconstruction. Radiologists will be confronted more frequently with such images and the demand by clinicians to produce them. It is thus important to be familiar with some technical details of the reconstruction process, particularly shading techniques, and potential applications in order to improve the effectiveness of these techniques. Here we describe the applications and technical details of three-dimensional reconstruction of CT or MR data.

Applications of three-dimensional reconstruction

Several applications for three-dimensional rendering of CT and MR data have been proposed in the last few years. These were mainly based on diseases with gross abnormalities of the skeleton. Three-dimensional rendering,
There are several approaches to the three-dimensional rendering of CT, MR [17] and scintigraphy data [10]. The steps of the rendering procedure are given in Fig. 1. To compensate for the deterioration in quality from partial volume effects or signal fall-off with surface and circumferential coil MR imaging, preprocessing methods of the original data set can be applied prior to reconstruction. These include linear low-pass filtering, non-linear filtering, signal fall-off compensation in MR images (normalisation), edge smoothing and subtraction of T1- from T2-weighted data (Fig. 2). Preprocessing usually alleviates the segmentation process.

Two basic groups of reconstruction or rendering techniques can be identified: surface rendering and volume rendering.

Surface rendering

Surface rendering methods are based on the data of boundaries of certain objects [18]. Since computation is accomplished with a subset of the entire data only, surface rendering is a fast method. Surfaces can be represented using many small triangles or rectangles (i.e. the polygon tiling or directed-contour representation method) or as a uniform matrix of non-cubic (anisotropic) or cubic (isotropic) voxels (i.e. the binary voxel or cuberelle representation method [19]). The directed-contour methods have the advantages of a very short computation time and considerably reduced storage capacity [20]. This enables all models to be rotated in real time on the monitor around several axes.

The voxel representation method yields the best results using cubic voxels. If the raw data do not consist of cubic voxels these can be created using linear interpolation [21]. This forms additional slices, enabling a division into cubes. The advantage of using cubic voxels is the improved object contour smoothness of the rendered image.

Identification [19] of different objects in a stack of images is accomplished by segmentation techniques. Different methods of segmentation are available. Tracking is a method of drawing lines around certain regions, either completely manually or partially manually, by setting seed-points at important anatomical landmarks that are subsequently automatically connected (Fig. 3). Region growing (auto-disarticulation) uses a method that is able to identify the boundary of a given structure with signal similarities and delineate it automatically (Fig. 3). Using thresholding as a segmentation technique, a certain limit of voxel values is defined as a selectivity criterion. A voxel is identified by an intensity threshold attribute. With this technique, only voxels with a certain attenuation or signal intensity value are used for reconstruction. All voxels within the given range are allocated to the object, the rest being excluded (i.e. binary segmentation) (Fig. 4).

Segmented objects can be further separated from others by disarticulation. Drawing disarticulation lines is usually accomplished using manual or partially manual tracking methods on a slice-by-slice basis.

A more sophisticated object definition method identifies several threshold ranges, thus being able to classify several objects in one step. This probabilistic or statistical thresholding classification is usually used for CT data [22]. The data set may be classified into three basic tissue types (i.e. fat or air, soft tissue and bone) and interfaces. Threshold segmentation is limited by partial volume averaging effects causing artificially low or high pixel values. Therefore, the initial threshold setting is critical for the quality of the rendered image. Choosing thresholds that are too low results in artificial surface gaps; settings that are too high result in fusion of adjacent surfaces [23].

More advanced approaches are necessary for satisfactory segmentation of MR data, since several tissues show signal similarities depending on the applied sequence. Multispectral methods and methods based on two sets of raw data with different relaxation time weightings have been introduced. Combinations of signal intensity probability and automatic recognition of connectivity (edge detection, e.g. the Marr-Hildreth operator algorithm [24]) will probably be the method of choice for the future [25].

To simulate a three-dimensional impression of surfaces, a mathematical computation of the data is carried out. It assigns every voxel a new grey value as though light from one or several sources were illuminating the object (e.g. Phong illumination [26]) and being diffusely reflected. This process is called opaque shading and is based on the negative distance between the visible voxel and the observer (depth) or the orientation angle of a surface (surface-normal).

Pure depth shading for medical purposes has yielded poor results and is rarely used any longer (Fig. 5a). Surface-normal shading has proved to be superior and several subtypes have been described. One surface-normal shading algorithm evolves the surface-normal from the position matrix assigned to the sagittal body axis (z-buffer) (Fig. 5b). Another surface-normal algorithm has been suggested by Höhne [27]. He evolved the surface-normal based on the grey values of the surrounding voxels of a given area (grey-level-gradient shading) (Fig. 5c). A more sophisticated grey-level-gradient algorithm computes the gradient from a variable number (6 to 26) of neighbouring voxels, adapting to the object's thickness (adaptive grey-level-gradient shading). This algorithm shows fewer arte-