Recent Advances in Multidimensional 3D/4D Breast Imaging

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Introduction

Three-dimensional (3D) mammasonography is the most recent development in breast ultrasound imaging and intervention, providing additional aspects to conventional two-dimensional (2D) sonography: completely new superior diagnostic information to study a breast mass and the surrounding tissue in three orthogonal planes. Four-dimensional (4D) ultrasound offers real-time 3D rendered image information and is taken as a basis of multidimensional imaging of the breast. In the following section about 3D and 4D breast ultrasound (US), after a short introduction to technical considerations, multidimensional imaging of solid benign and malignant breast lesions, 3D targeting, and real-time 4D breast biopsy technique are discussed.

3D Ultrasound Technique and Display

Two principal techniques and the combination of both exist to obtain three-dimensional (3D) ultrasound (US) information: manual or automatic scanner movement with echo data processing along the US beam. All demonstrated cases were investigated with a linear array 2D and 3D US volume transducer, 5–13 MHz, with a 29° volume sector angle, combined with the Voluson 530D and 730 (GE Medical Systems Kretz Ultrasound, Zipf, Austria). The Voluson technique offers the option to acquire a 3D US volume data set automatically with one and the same transducer without freehand movement of the probe. In about 3 s the system obtains the entire 3D data volume set (about 10 MB) and displays the information in a multiplanar image display mode.

Multiplanar Display Mode

The multiplanar representation uses the 3D US information from three planes (A, B, and C plane) that cut the voxel and are orthogonal to each other. The A plane shows

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the original scan plane during typical 2D US investigation and volume acquisition. The B plane is orthogonal to A and C and offers the typical rectangular US information of 2D scanning, for example, the sagittal or transversal plane. Completely new diagnostic information is obtained by the coronal plane (C plane), which is orthogonal to A and B. Furthermore, the system allows navigation through the entire acquired volume conducting parallel interactive movement through the image slices. In all three planes, a colored dot (A, yellow; B, orange; C, blue) indicating an identical voxel can be identified in every activated plane in the volume of interest (VOI). Synchronous parallel image movement in all the corresponding orthogonal planes can be observed as the information in the VOI rectangle is updated. A dynamic analysis of the 3D-acquired US information of an anatomical detail is available and is easier to understand; for example, complex collecting duct branching.

Rendering Modes

The acquired US volume data allow a variety of 3D rendering modes, and the most effective for visibility of the biopsy needle inside the 3D data set are transparency modes. Fading, for example, between maximum or minimum modes, gives reliable information of ductal anatomy and pathology such as intraductal papilloma. Combined with an animated rotation of the transparent rendered tissue block, the position of the needle in relation to the lesion can also be better evaluated.

2D and 3D US Characterization of Solid Breast Lesions

All 2D and 3D US investigations were performed with the patients in supine position with elevated arms. The typical 2D US analysis of breast lesion shape, width-to-depth ratio, margin characterization, lesion compressibility, lesion echogenicity, and echo texture, followed. The additional 3D US information first displayed in the multiplanar mode offers the new coronal plane lesion aspect ancd allows marking of the different breast masses by retracting and compressing lesion patterns as described by Rotten and colleagues [1, 2].

Fibroadenoma

3D US gives reliable information about the lesion shape. Fibroadenomas often show a round base, like a coin positioned parallel to the skin, embedded by breast tissue. Due to their transversal width-to-sagittal depth ratio of more than 1 on 2D cross-sectional images, they have a more cylindrical morphology than assumed by 2D US. Also, real-time 2D US usually is not sufficient to give a clear understanding of the 3D lesion aspect in cases of the more complex bases of fibroadenomas with lobulation of their surfaces and dumbbell-like or irregular aspects. In about 3–4 s, the Voluson technique offers a 3D multiplanar image of the fibroadenoma without any dependence on long or short axis lesion diameter or angulation. Different measurements of width and depth distances can be accurately obtained, guided by all three planes.

3D US volume datasets show more objective fibroadenoma compressibility than 2D US, because during echo palpation a well-defined embedded lesion is movable and the probability increases that 2D US causes depth–axis diameter measurement in dif-

ferent positions, with the consequence of measuring incorrect distances. Comparing the 3D morphology of the lesion before and after compression with 3D US datasets provide correct measurements of comparable slices.

Invasive Breast Carcinoma

According to the study of Rahbar et al. [3], 2D US features that characterize lesions as malignant are irregular shape (61% malignant), microlobulated (67% malignant), spiculated (67% malignant), and a width-to-depth (anteroposterior dimension) ratio of 1.4 or less (40% malignant). Most of the time the tumor center is characterized by a homogeneous echo-poor fibrohyalinosis followed by a dorsal shadowing due to ultrasound energy absorption. The echo-rich margins are the expression of many different tissue components of tumor cells, fibrous strands, fatty tissue, and surrounding glandular parenchyma indicating the tumorous growth and infiltration zone. Mammography clearly shows this stellate infiltration pattern with the architectural distortion of the neighboring structures.

3D US is the first ultrasound imaging modality that offers simultaneously the coronal, transversal, and sagittal plane for eliminating the architectural distortion as in mammography. Although 2D US shows signs of disrupted connective tissue layers and changes of the shape and disruption of the superficial fascia in the transversal and sagittal planes, these signs are less impressive compared with the tissue distortion and retraction presented in the 3D coronal plane. Even in stellate carcinomas smaller than 1 cm in diameter, the retraction pattern is visible in the coronal plane.

In particular, invasive lobular carcinomas sometimes develop without a mammographically and sonographically visible dominating mass. In such a situation the coronal plane helps to visualize the architectural distortion and enables understanding of the underlying pathology. Therefore, dense, palpable, especially asymmetrical breast tissue should be investigated by 3D US to detect architectural distortion. When invasive lobular carcinoma forms a more circumscribed mass or tends to produce multifocal lesions, these tumorous lesions have a similar ultrasound aspect such as an invasive ductal carcinoma. Although Rotten described the retraction pattern highly characteristic for malignant masses, we have to consider benign differential diagnoses such as the radial scar, sclerosing adenosis, or postoperative scarring.

3D Targeting Technique

The sonographic visibility of a suspicious lesion is the basis for an ultrasound-guided biopsy. 3D breast US offers a correlation of typical “freehand” 2D US guided core or fine-needle biopsy and hookwire localization of palpable and nonpalpable lesions to optimize tissue sampling and to reduce the miss rate [4, 5]. The consequence of 3D targeting should be a reduction of needle passes without an increase of miss rate due to objective 3D demonstration of correct or incorrect core or fine-needle position [6]. First, a 3D US volume dataset is acquired to study the morphology of the lesion. The multiplanar scan plane analysis offers comprehensive information of the lesion and the surrounding structures. For large-core needle biopsy (14 gauge) with local anesthesia, a 3-mm skin incision is performed. In typical freehand 2D US guidance [7], the needle path should be as horizontal as possible to optimize visualization of the

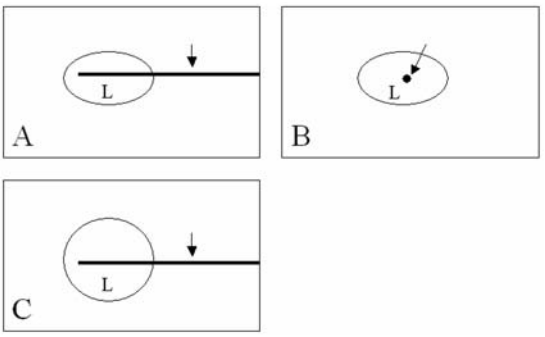

Fig. 1. Multiplanar display and 3D-targeting: needle (*arrows*) in all three planes (*A*, sagittal; *B*, transversal; *C*, coronal plane) inside the lesion (*L*)

needle length and needle tip. Via the 13-gauge coaxial cannula, a 14-gauge core needle is positioned in front of the lesion. After a 22-mm core needle stroke using a BIP (High Speed-Multi) biopsy gun (Biomed Instrumente und Produkte, Türkenfeld, Germany), the Voluson technique offers the option to acquire a 3D US volume data set with one and the same transducer without freehand movement of the probe. In about 3 s, the system acquires the entire 3D data volume and displays information about the needle position in relation to the lesion accurately in a multiplanar imaging mode. This needle position check in all three planes is called 3D targeting [8].

Real-Time 4D US Breast Biopsy

A newly developed software allows real-time 4D US needle guidance during breast biopsy. The permanently acquired real-time 4D US volume data are displayed in a multiplanar scan plane analysis mode. Compared to conventional freehand 2D, US needle guidance real-time 4D offers additional permanent information of all three planes in the multiplanar display mode, a rendered image of the breast lesion, and the needle position. The three-dimensional permanent analysis of lesion position as well as needle position in all three planes allows one to navigate the core needle in an optimal prefire position. After the core needle stroke, 3D targeting follows, showing the correct or incorrect needle position.

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