GE Healthcare

3D/4D Ultrasound Breast Imaging

C.F. WEISMANN

Diagnostic and Interventional Breast Department

Private University Institute of Diagnostic Radiology,
St.Johanns Hospital Landeskliniken Salzburg, Austria

Introduction

High quality two-dimensional (2D) breast imaging is the basis for screening for breast cancer with ultrasound (US). 3D/4D mammasonography is the most recent development in breast ultrasound imaging providing additional aspects to conventional 2D sonography: completely new superior diagnostic information such as the ability to study a breast mass and the surrounding tissue in 3 orthogonal planes, or to obtain new information about the mean blood flow intensity or vascularization of breast lesions by evaluation of the 3D color histogram. 4D ultrasound offers almost 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, display options, volume contrast imaging (VCI), Volume Calculation (VoCal), Tomographic Ultrasound Imaging (TUI), 3D-High Definition Flow (HD-Flow), 3D-Power- and color Doppler, 3D-targeting and realtime-4D breast biopsy techniques will be discussed.

3D ultrasound technique and display options

Two principle techniques and the combination of both exist to obtain 3D 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, 6-16 MHz, with a 29° volume sector angle combined with the Voluson 730 Expert (GE Medical Systems Kretz Ultrasound, Zipf, Austria).
The Voluson technique offers the option of acquiring a 3D US volume data set automatically with one and the same transducer without freehand movement of the probe. In about 3 seconds the system obtains the entire 3D data volume set (about 10 MByte) and displays the information in a multiplanar image mode.

Multiplanar mode

The multiplanar representation uses the 3D US information from the three planes (A-, B- and C-plane) that cut the voxel which are orthogonal to each other (Figure 1) (1,2).
The A-plane shows 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 two-dimensional scanning, for example, the sagittal or transversal plane. The 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 3 planes a colored dot (A: yellow, B: orange, C: blue) indicating an identical voxel can be directed in every activated plane into the volume of interest (VOI). Synchronous parallel image movement in the corresponding orthogonal planes can be observed and shows the VOI reformatted in rectangular fashion. A dynamic analysis of the 3D acquired US information of an anatomical detail is available and is easier to understand, e.g., complex collecting duct branching.

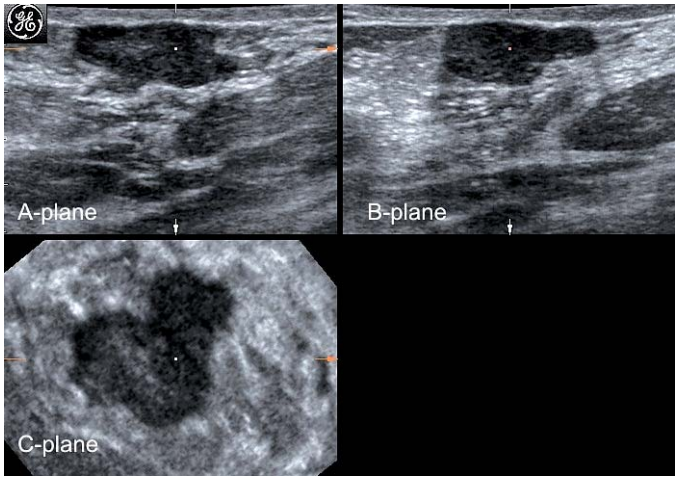

Figure 1: Multiplanar display mode of a fibroadenoma. The A-plane is the 2D scanplane information. The B-plane is perpendicular to A and C. The C-plane is the coronal plane and shows a compressive pattern of the fibroadenoma

Niche mode view

The 3D US data are represented as a "cut-open" view of, e.g., the interior view of a tumorous lesion and its surrounding tissue (2). This mode also impressively demonstrates the relationship of the converging subareolar collecting ductal system and the mamilla. After 3D US data acquisition, the volume offers the entire nipple area and the retromamillary region in one volume. An optimal time-gain adjustment combined with contrast resolution imaging (CRI) is necessary to reduce shadowing behind the nipple area for full diagnostic information of the ductal system.

Surface mode

The surface mode provides the assessment of rendering surface structures (2). A good result of surface rendering can be obtained by studying the inner structures of a cyst or an intraductal papilloma outlined by echo-poor fluid. The gray values of the surface are identical with the gray values of the original scan. Impressive surface information on a more complex three dimensional lesion morphology can be acquired.

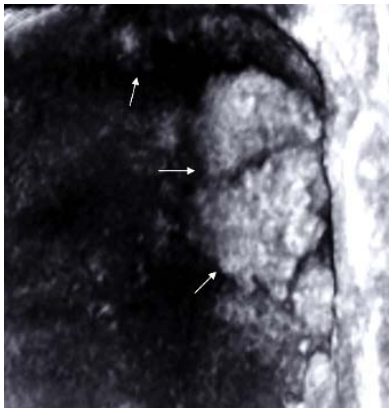

Figure 2: Surface mode presentation of an intracystic papillary breast cancer (→)

Tranparency mode

The acquired US volume data allow three-dimensional rendering using transparency mode and fading, e.g., between a maximum or minimum mode adjustment (2). This mode gives reliable information of ductal anatomy and pathology, e.g., intraductal papilloma. Additionally, an animated study distinctly illustrates ductal branching or intraductal pathological structures and gives information on their spatial relationships. The transparency mode makes a biopsy needle inside the acquired 3D US data set visible. Combined with an animated rotation of the transparent rendered tissue block, the position of the needle in relation to the lesion can be evaluated.

Glass body rendering

Glass body rendering is a special transparency mode, which makes the grayscale data transparent and displays the color data of 3D high definition flow (HD-Flow), 3D Power- Doppler and 3D color Doppler in surface mode. This mode offers the basis for detailed study of the three-dimensional vascular supply of the lesion and the surrounding breast tissue.

Inversion mode

Echo-poor breast lesions are suitable for rendering by inversion mode technology (Figure 3). The volume of interest (VOI) must cover the entire lesion. The inversion render mode shows the lesion in a 50% mixed surface smooth and 50% gradient light algorithm as a white-colored 3D model. The threshold level "low" must be customized on the one hand to suppress the echogenic constituents in the VOI, on the other hand to present the echo-poor lesion in a 3D-surface algorithm. The additional echo-poor structures, not related to the lesion, can be removed by the electronic scalpel. To understand what structures are not related to the lesion, the entire rendered VOI must be rotated, e.g., around the y- and/or the x-axis.

The inversion mode is a tool which offers quick access to the three-dimensional morphology of the investigated breast mass. The shape of a lesion is an important diagnostic criterion in differentiating between benign and malignant breast tumors.

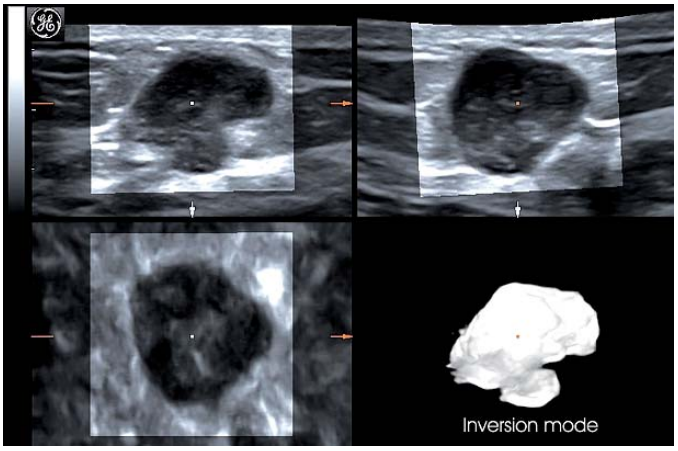

Figure 3: Static 3D multiplanar image of an invasive ductal breast cancer with the inversion mode information of the volume of interest (VOI)

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 and allows marking of the different breast masses by retracting and compressing lesion patterns as described by Rotten and colleagues (3,4).

Fibroadenoma

The typical two-dimensional US appearance of a fibroadenoma is characterized by a well-defined ovoid or roundish (70%), partly lobulated, homogenous hyporeflexive mass (76%), with an occasionally thin hyperechogenous boundary to the surrounding tissue forming a pseudo-capsule. Lateral shadowing (65%) and hyperreflexivity behind the fibroadenoma (in 25% to 38%) may be visible (Figure 1). 10% show dorsal hyporeflexivity (5). The typical 2-dimensional cross-sectional ovoid shape with the long axis diameter parallel to the skin and a transversal width-to-sagittal depth ratio of >1.4 can be found in about 70%. In 30% a lobulated polycyclic fibroadenoma with slightly inhomogenous internal echogenicity may occur. Mostly the short axis depth diameter can be compressed in about 20%. As described by Rahbar (6) the most reliable 2D US features characterizing a benign lesion are of round or oval shape (94% benign), circumscribed margins (91% benign) and a width-to-depth (anteroposterior dimension) ratio greater than 1.4 (89% benign).

3D US gives reliable information of the lesion shape (1,2). 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 >1 on 2D cross-sectional images they have a more cylindric morphology than assumed by 2D US. Also real-time 2D US is usually not sufficient to give a clear understanding of the three-dimensional lesion aspect in cases of the more complex bases of fibroadenomas with lobulation (Figure 1) of their surfaces and dumbbell-like or irregular aspects. In about 3-4 seconds, the Voluson technique offers a 3D multiplanary 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 different positions, with the consequence of measuring incorrect distances. Comparing the three-dimensional morphology of the lesion before and after compression with 3D US datasets provides correct measure-ments of comparable slices.

Rotten and colleagues (3,4) investigated 186 solid breast lesions and described 2 predominant tissue patterns surrounding the breast lesion and visible in the coronal plane: the compressive pattern associated with benign lesions such as fibroadenomas (Figure 1) and the retraction pattern, which was highly suggestive for malignancy. The 3D statistical performance to differentiate malignant from benign by the criteria of compressive and retraction pattern showed in the study of Rotten et al. a high specificity (0.938), high sensitivity (0.914) and high predictive values (positive pv: 0.869, negative pv: 0.960) (Table 1).

The statistical data of our study group of 263 solid breast lesions investigated for the compression pattern- (indicating benignancy) or retraction pattern-sign (indicating malignancy) are presented in Table 1.

	Statistical data [Rotten et al., 1999 (4)] n = 186	Statistical data [Weismann et al., 2002] n = 263
Sensitivity	0.914	0.995
Specificity	0.938	0.842
Positive predictive value	0.869	0.919
Negative predictive value	0.960	0.99

Table 1: Statistical analysis of 3D-US data on compressive pattern and retraction pattern to differentiate benign from malignant solid breast lesions compared with the results of the publication of Rotten et al.

The compressive pattern of a fibroadenoma shows a thin or different wide hyperechogenous boundary to the surrounding tissue caused by a space-occupying lesion. Sometimes forming a pseudo-capsule, developed by distortion and compression of the surrounding structures, a fibroadenoma does not infiltrate the neighboring tissue.

Invasive breast carcinoma

The macromorphological growth pattern of breast cancer is heterogeneous. Invasive breast cancer can show a stellate and/or nodulary aspect, a circumscribed mass, a diffuse infiltrating growth pattern, or can be developed as a papillary carcinoma or a rare intracystic carcinoma.

75% of invasive breast cancers are invasive ductal carcinomas frequently arising in the extralobular portion of the terminal duct. Macropathologically, they usually appear as a solid nodulary mass with stellate margins due to the tumorous infiltration into the surrounding tissue followed by fibroplastic reaction with architectural distortion. Additional intraductal tumorous spread combined with intraductal microcalcifications often can be found. In 10 to 15% of the cases, invasive lobular carcinomas arise from the epithelial layer of the lobule.

They tend to grow diffusely along ducts, vessels and Cooper ligaments like wallpaper combined with architectural distortion, and frequently form diffuse palpable lesions, skin thickening (15%) and skin retraction (21%). In contrast, the invasive mucous carcinoma and the invasive medullary carcinoma (5-7% of all invasive breast cancers) show smooth marginated borders with a pseudo-capsule and imitate benign lesions like a fibroadenoma.

According to the study of Rahbar (6) 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 homogenous 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 which simultaneously offers the coronal, transversal and sagittal plane for eliminating the architectural distortion as in mammography (1,2). 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 coronal plane (Figure 4). Even in stellate carcinomas smaller than 1cm in diameter, the retraction pattern is visible in the coronal plane.

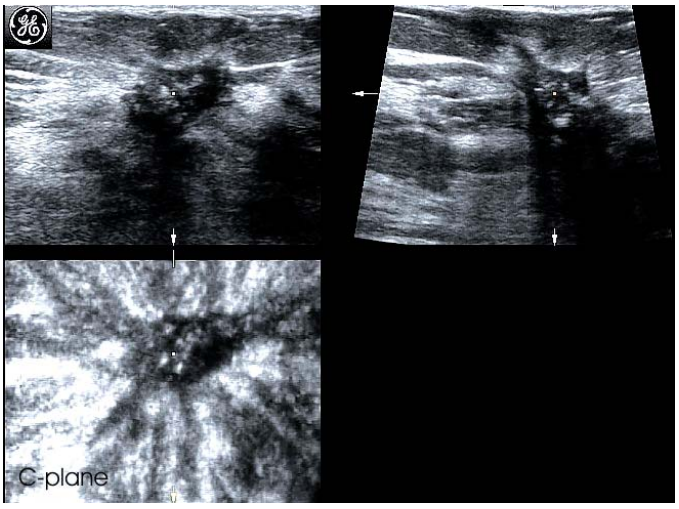

Figure 4: Invasive ductal breast cancer with retraction pattern sign in the C-plane; Intratumoral microcalcifications are visible (bright echogenic dots in the echopoor tumour center in all 3 planes)

Multifocal breast cancer results from different invasive cancer origins of the ductal system of one glandular lobe and is a common finding. Translating and rotating the entire acquired 3D volume data of a breast cancer and the surrounding tissue in the multiplanar display mode, makes the underlying process of multifocal breast cancer disease easier to understand (7).

In particular, invasive lobular carcinomas sometimes develop without 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 aspects such as an invasive ductal carcinoma. Although Rotten described the retraction pattern as highly characteristic for malignant masses, we have to consider benign differential diagnoses such as the radial scar, the sclerosing adenosis or postoperative scarring.

Static Volume Contrast Imaging (VCI)

Static volume contrast imaging offers to study a static three-dimensional dataset with pre-selected slice thickness (4DView: 1-20 mm) at the same time in all three planes in different render algorithms. The benefit of this technique is that it enhances the contrast between the lesion and the background structures with the aim of optimizing the contours in order to make accurate measurements and correct differential criteria analysis.

Volume Contrast Imaging (VCI)

Volume Contrast Imaging is a real-time 4D ultrasound technique which offers thick- slice rendering (6-10 mm slice thickness) or thin-slice rendering (2-4 mm slice thickness) (2,8) . The render algorithm is a combination of surface- and transparency mode. The Voluson 730 technology offers VCI in the typical 2D ultrasound accessible planes as well as in the coronal plane. The advantage of the VCI technique compared with conventional 2D ultrasound is the contrast-enhanced representation of almost isoechogenic lesions compared to the background. As a consequence, VCI provides an accurate measurement and safe needle guidance into, e.g., an echo-poor fibroadenoma surrounded by echo-poor fatty tissue.

VCI-C is the preferred technique for studying lesions and the surrounding tissue under 4D-related sonopalpation and dynamic 4D investigation (8). As a consequence of this, for example, VCI-C is able to help to differentiate between a spiculation of the breast mass and an US artifact caused by shadowing, coming up from the borderline between a fatty tissue lobule of midechogenicity and the hyperechogenic fibroglandular constituents mimicking a spiculation. Sonopalpation is the act of compressing and decompressing the breast tissue with the finger and monitoring the movements between the different tissue layers with VCI-C. Dynamic 4D-US studies present the imaging information, coming up from a circular movement of the transducer under the C-plane aspect of the lesion and the surrounding breast tissue.

Volume Calculation (VoCal)

The "4DVIEW" is a workstation-like integrated computer program that offers volume calculations (VoCal). The basic principle of VoCal is to combine geometric surface information with the volume dataset of a lesion (2,7,9). On the condition that the lesion is circumscribed with clear contours, the VoCal software enables automated or manual volume calculation. The surface geometry is defined by rotation of an image plane around a fixed axis. The surface geometry can be visualized as a colored surface, a wire mesh model or a rendered grayscale surface. Well-defined lesions including fibroadenomas, papillomas or rare, well-defined breast cancers such as medullary or mucous carcinomas can be evaluated by VoCal.

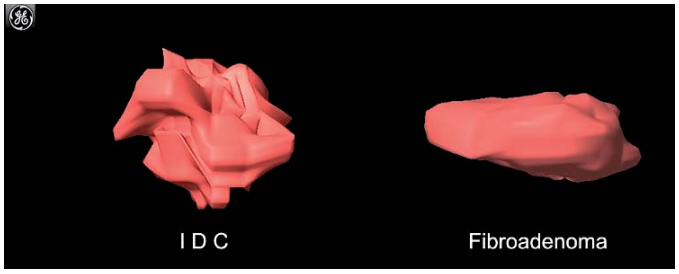

Figure 5: Geometric surface information obtained by VoCal from an invasive ductal breast cancer (IDC) and a fibroadenoma

Tomographic Ultrasound Imaging (TUI)

Tomographic ultrasound imaging (TUI) presents the diagnostic information of a static 3D dataset in two-dimensional documentation e.g., a thermoprint or laserprint, comparable with CT or MR scans. A topogram precisely shows the spatial position of the slices obtained from the 3D data set and the customized distance between the different slices. TUI is the primary foundation for offering comprehensive diagnostic information of the three-dimensional extent of a lesion on the basis of a two-dimensional display (Figure 6). To optimize the information transfer, TUI makes it possible to slice and to document the lesion in all three planes.

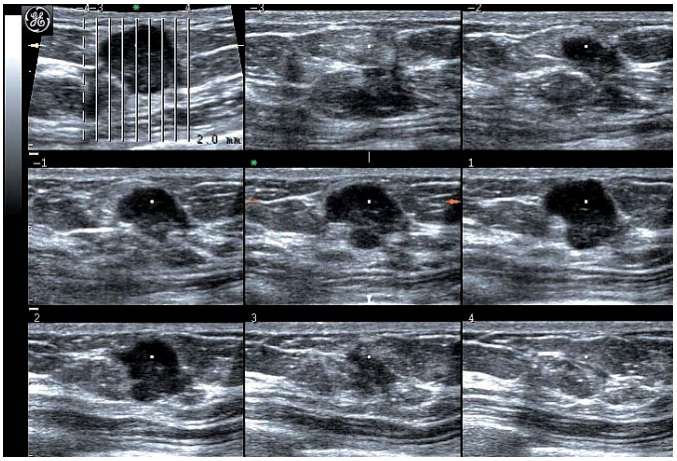

Figure 6: Invasive ductal breast cancer presented with TUI; The topogram of the A-plane shows the slice positions and the slice distances (in this case 2 mm)

3D Power-Doppler, 3D Color-Doppler, 3D High Definition Flow (HD-Flow)

The vascularization of a breast lesion can be investigated using 3D technique with power-Doppler (amplitude-based color-Doppler sonography) and frequency-based color-Doppler sonography. High definition flow (HD-Flow) is a color Doppler technique which on the one hand offers a high slow flow detection comparable to power-Doppler and on the other hand gives information about the blood flow direction.

The neovascularization of a carcinoma with an irregular vascular pattern, arterio-venous shunts and missing vessel-autoregulation in contrast to normal breast tissue vessels is the background for many studies with two-dimensional ultrasound and computer-assisted quantitative color Doppler analysis aiming at a differentiation between malignant and benign breast lesions (2,10,11,12). The morphological pattern of tumor vessels and tumor feeding vessels is an approach for 3D HD-Flow and 3D power-Doppler studies. 3D power-Doppler imaging provides the analysis of blood flow and three-dimensional vascularization patterns of the entire tumorous lesion without the limitation of scanning only two-dimensional planes, including the potential problem that the most representative slice might not be scanned. 3D HD-Flow additionally shows the blood flow direction in the three-dimensional vascular architecture. In combination with glass body rendering, the vascular architecture in relationship to the tumor extent and the surrounding breast tissue can be investigated (Figure 7).

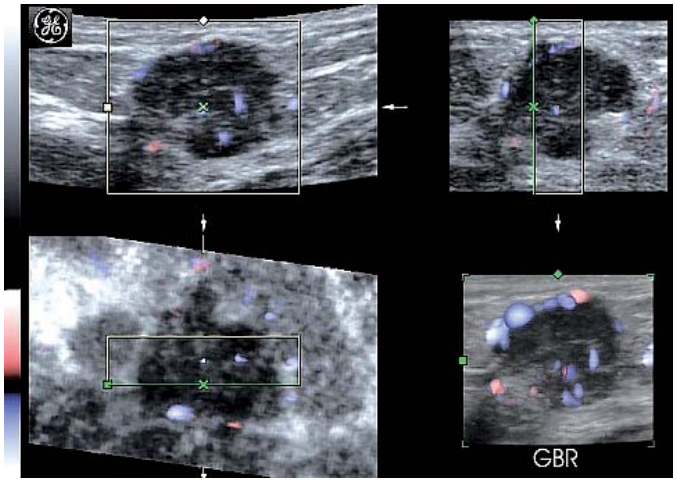

Figure 7: Glass body rendering (GBR) of the three-dimensional vessel distribution within the VOI of the invasive ductal breast cancer of Figure 6

Suppressing the grayscale parameters, a three-dimensional angiogram will be obtained (Figure 8). 3D power-Doppler volume information offers an effective tool for evaluating the color histogram and the spatial distribution of the vessels inside and outside of the malignant or benign tumor. 3D reconstructions of the color volume data are suitable for studying the three-dimensional vessel distribution and the potential irregularities in vessel shape (2,7,9).

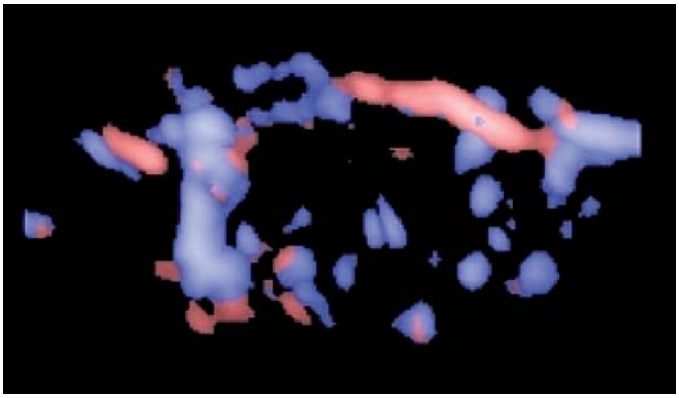

Figure 8: 3D angiogram of the invasive ductal breast cancer of Figure 7

The color histogram gives information about the vascularization index (VI), the flow index (FI) and the vascularization-flow index (VFI) inside a user-defined volume of interest (VOI). The vascularization index (VI) gives information in percent [%] about the amount of color values (vessels) in that volume of interest. The VI is calculated by dividing the figure of color values by the figure of total voxels minus the background voxels of selected VOI (Table 2).

The dimensionless flow index (FI) measures the mean blood flow intensity. The figure ranges from 0 to 100. FI is calculated as the ratio of weighted color values (weighted by their amplitudes) to the number of the color values. The vascularization-flow index (VFI) gives combined information of vascularization and mean blood flow intensity. The figure of the VFI is also dimensionless and ranges from 0 to 100. It is calculated by dividing the weighted color values (weighted by their amplitudes) by the total voxels minus the background voxels (Table 2).

COLOR-HISTOGRAM

Vascularisation Index [%] (VI)	=	color voxels / (total voxels - background voxels)
Flow Index [0,100] (FI)	=	weighted colour values / color values
Vascularisation-flow Index [0,100] (VFI)	=	weighted color values / (total voxels - background voxels)

Table 2: Mathematical formulae of the color-histogram parameters VI, FI and VFI

In 1997 Madjar and Jellins (13) described the contrast enhancement flow from the periphery to the center of malignant as well as benign tumors by 2D US studies. In that study the carcinomas showed this pattern in a more pronounced way, with the malignant neovascularization revealed as having a distinct radiating pattern and a vascular corona, equivalent to the growth zone of the tumor, visible in the echo-dense rim seen on B-mode US. 3D power-Doppler combined with the representation of three-dimensional vessel architecture, VoCal, color histogram and the additional option of intravenous contrast enhancers are important for further studies of tumor neoangiogenesis to determine their diagnostic efficacy for differentiation of benign and malignant lesions.

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 non-palpable lesions in order to optimize tissue sampling and to reduce the miss rate (1,2,14,15). The consequence of 3D-targeting should be a reduction of needle passes without the increase of miss rate due to objective 3-dimensional demonstration of correct or incorrect core- or fine needle position (1,2,15). 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) local anesthesia is used. In typical freehand 2D US guidance (17), the needle path should be as horizontal as possible to optimize visualization of the 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 GesmbH, Türkenfeld, Germany) the Voluson technique offers the option of acquiring a 3D US volume data set with one and the same transducer without freehand movement of the probe. In about 2-3 seconds the system acquires the entire 3D data volume and displays the information of the needle position in relation to the lesion accurately in a multiplanar imaging mode. This needle position check in all 3 planes is called 3D-targeting (Figure 9) (1,2,18).

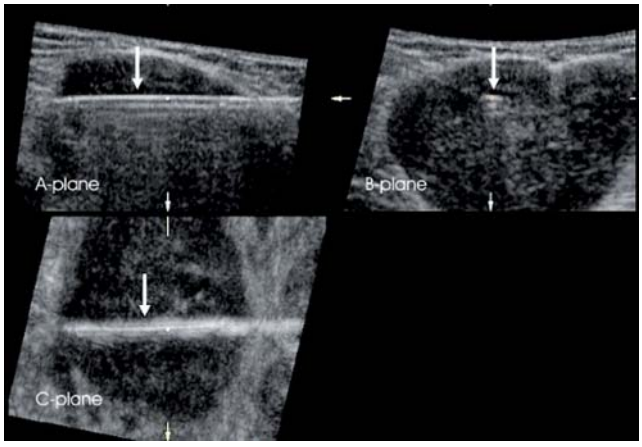

Figure 9: Multiplanar display and 3D-targeting in a 14G large core needle biopsy of an axillary lymph node metastasis: needle (→) in all 3 planes inside the metastatic lymph node (A-plane: sagittal, B-plane: transversal, C-plane: coronal)

Real-4D US Breast Biopsy

Dedicated software allows real-4D US needle guidance during breast biopsy (8). The permanently acquired real-4D US volume data are displayed in a multiplanar scan plane analysis or in a combination of A-plane and rendered C-plane mode (1). Compared to conventional freehand 2D US needle guidance, real-4D also offers permanent information on all three planes in the multiplanary display mode, a rendered image of the breast lesion and 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 pre-fire position. After core-needle stroke, 3D-targeting follows unveiling the correct or incorrect needle position.

Conclusion

As mentioned in the topics above, 3D/4D ultrasound of the breast is a helpful diagnostic and interventional imaging tool, fit for daily diagnostic practice and an important addition to two-dimensional breast ultrasound offering new diagnostic aspects for differentiating benign from malignant breast lesions. 3D US datasets offer perfect documentation of interventional procedures and provide a reliable basis for follow-up investigations of breast lesions.

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GE Medical Systems Ultrasound – United Kingdom
Fax: (+44) 1234 266261, Tel: (+44) 1234 340881

GE Medical Systems – America:
Milwaukee, WI, USA - Fax: (+1) 262 544-3384

GE Medical Systems – Asia:
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Re-think, Re-discover, Re-invent, Re-imagine.

GE Ultraschall Deutschland GmbH & Co. KG
Beethovenstr. 239, D-42655 Solingen

Fax: (+49) 212-28 02 28
Tel: (+49) 212-28 02-0

www.gehealthcare.com

GE imagination at work

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