Automated analysis of 3D echocardiography

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7 Discussion and conclusions

7.1 | Research objective

objective

Assessment of left ventricular function is important in clinical decision making, evaluation of therapeutic effect and determination of prognosis. Automating this assessment may improve the diagnosis and treatment, and reduce its costs through reduction in time and labour needed for the analysis. It may also reduce interobserver and interinstitutional variability and improve the reproducibility.

We aimed at automating the assessment of left ventricular function using 3D echocardiography, especially by employing the cost-effective design of the fast rotating ultrasound (FRU) transducer.

7.2 | Contributions

semi-automatic quantification

Most important in evaluation of LV function is the estimation of the LV volume over the full cardiac cycle. We have shown that this full cycle analysis can be achieved semi-automatically using a method based on dynamic programming and pattern matching with good correspondence to our golden standard, without most of the geometrical assumptions that are made in analysis of 2D echocardiography.

automated tracking

The main source of errors in the full cycle analysis lay in the weak temporal model for mitral valve motion. We studied automatic analysis of this motion by tracking the mitral valve hinge point using multidimensional dynamic programming and apodized block matching in VCR recorded 2D echocardiograms. It shows that this tracking can be reliably done over the full cardiac cycle with an accuracy and precision that are close to those of the human observer. Its versatility allows it to be tuned to either low level image structures such as speckle, or more coarse anatomical structures such as the septal mitral valve hinge point, and it has the conceptual ability to be applied to 3D tracking. The robustness of the tracking in low quality and relatively low frame rate interlaced VCR recorded images is promising for future application in 3D echocardiography using the FRU transducer, which has better image quality but an effectively lower temporal resolution in 3D.

image reconstruction

The FRU transducer features high quality 2D frames, compared to competing 3D matrix transducers. However, reconstruction of the 3D image sequences for visual inspection of the LV geometry and function, is challenging because of the 2D nature of the acquisition and the irregular and sparse distribution of the 2D frames in 3D+T space. We proposed a reconstruction method based on normalized convolution to improve on regular trilinear interpolation using temporal binning. Our new method deals with the 4D (3D+T) nature of the data and visually improves the temporal delineation of anatomical structures. The interpolation framework is flexible and has room for improvements in development of adaptive filters that optimize the interpolation spatially and temporally. Adjustment of the kernel dimensions to the sparseness of the data can improve the interpolation both in dense and sparse regions.

The interpolation of the FRU data to volumetric sequences allows application of generic 3D+T analysis methods. We developed a method for automatic detection of the LV long axis and the mitral valve plane in 3D echocardiography. The detection of these skeletal features of the LV can be done with good accuracy and precision, promising applicability as an initialization step for fully automatic model based segmentation approaches. The method showed good agreement with manual annotations and may therefore save valuable time and labour in such applications, removing also interobserver variability.

automatic initialization

Finally, fully automatic segmentation of the left ventricle in 3D echocardiography has been investigated using active appearance models. In this work, the value of the dedicated gray value normalization is reflected in the superior generalization of the normalized texture model. Matching optimization using Jacobian tuning substantially improves the accuracy of the detection and especially the lock-in range. These controlled matching experiments in in-vivo data show the feasibility of LV volume quantification using AAMs in 3D echocardiography and its future promise.

model based segmentation

Discussion | 7.3

In general, we have succeeded in developing several techniques that each bring analysis of 3D echocardiography further to its ultimate goals: making it more reliable, less observer dependent, cheaper and less labour intensive. Certainly, in near future echocardiography will improve technically, resulting in better image quality and higher frame rates available at a more affordable price, allowing better automated analysis. In this work, we have shown that automated analysis based on 3D echocardiographic data acquired with the cost effective FRU transducer can be competitive with commercial matrix transducer systems. We have proposed generic techniques for automated reconstruction, tracking, feature detection and segmentation that reduce interobserver variability and time of analysis, making analysis of 3D echocardiography more reproducible and cost effective.

Most of these techniques are applicable or extendible to related ultrasound mo-

general applicability

dalities. The automated segmentation and automated initialization procedures (chapter 2, 5 and 6) might directly be employed in 3D transesophageal echocardiography (TEE). Segmentation using AAMs might also be extended to simultaneous segmentation of multiple cardiac chambers as far as those can be visualized properly with 3D echocardiography. The 3D+T interpolation based on normalized convolution (chapter 4) might also be applicable to reconstruction of freehand 3D ultrasound in various clinical applications, e.g. in intraoperative neuro imaging. Future applications of the initialization procedure in chapter 5, might also be found in centerline detection in 3D vascular imaging, e.g. of the carotid arteries. Automated tracking based on multidimensional dynamic programming (chapter 3) can be of great value in most echocardiographic modalities in 2D and 3D. This feature-based tracking needs only a low frame rate and gross image structure, allowing it to complement or enhance the more common speckle-based tracking, which demands high frame rates and high inter-frame correspondence.

image quality

technical limitations

Currently, image quality is a major limitation in (automated) analysis of 3D echocardiography. Current transducers suffer from a relatively large footprint, often resulting in rib shadowing. Besides, shadows resulting from the lungs are an issue in apical acquisitions. These limitations restrict apical 3D echocardiography to imaging of the left ventricle only, especially in stress protocols, and even in the left ventricle major shadowing artifacts are often present. Transducer sensitivity and bandwidth are also compromised in current 3D transducers, resulting in suboptimal harmonic capabilities and higher levels of noise and artifacts than in 2D images. Furthermore, image resolution is limited, especially in the far field regions of the image. In FRU data, sparseness is also present due to the irregular sampling of the 3D+T space. The typical tradeoff between spatial and temporal resolution (volume frame rate) still poses a major limitation and keeps both below the desired level. This may soon be alleviated by massively parallel beam forming, but currently the only remedy is multi-beat fusion. This multi-beat fusion in similar near real-time solutions leads to stitching artifacts as a result of inter-beat variability and patient's, transducer or respiratory motion. These artifacts challenge the feasibility of locating the true endocardial border in these images, even by experts.

contrast agents

Enhancement of the endocardial border in 3D echocardiography can be achieved through the use of contrast agents for LV opacification. Although this may improve the visual distinction between blood and myocardium, it might not directly benefit automated analysis techniques. Contrast agents may render spurious edges in static images, that actually are a result of contrast swirls, complicating the automated detection. Besides, contrast agent concentration may vary during the acquisition and high concentrations may yield high attenuation, both resulting in variable contrast-to-tissue ratios. Automated techniques that combine a model-based approach (chapter 6) with an adapted edge detector may be most promising in analysis of these images.

Recommendations for future work | 7.4

Widespread use of 3D echocardiography will require robust and reliable analysis tools to ensure its value in diagnosis and clinical decision making. Improvements in these automated analysis techniques may be found in further investigation of the following directions.

Texture analysis | 7.4.1

As we observed in chapter 6, myocardial texture may differ widely across the position within a single acquisition as a result of rib or lung shadowing, the angle of incidence of the ultrasound beam, attenuation, anisotropy, near-field clutter, noise etc. In our case, this resulted in poor generalization of the texture model. Future work should be directed towards identification of these typical artifacts, such that a reliability measure can be taken into account for each image region. Much can be gained by temporal analysis of the data, revealing functional information from seemingly noisy speckle patterns. Also preprocessing, optionally integrated into the reconstruction process, for example using spatiotemporal adaptive filtering, might improve the essential signal-to-noise ratio in the relatively low quality ultrasound images.

Model based segmentation | 7.4.2

Despite any future improvements in ultrasound technology, 3D echocardiographic imaging will remain a challenge and associated with previously mentioned typical artifacts. Therefore, segmentation of the left ventricle in 3D echocardiography requires knowledge about the heart as an organ; its anatomy, physiology, its dynamics. Typical artifacts will mislead automated detection techniques, which should overcome partly missing data, false edges as a result of the reconstruction or shadowing and so on. Without any knowledge about the target object or organ, these artifacts cannot be overcome. As shown in chapter 6, statistical models, such as

AAMs, are a very elegant way of incorporating all this knowledge about anatomy, dynamics and appearance together with typical artifacts. Increasing the training populations will further improve the generalization capabilities of these models. Also, more efficient representation of textures may be found using e.g. wavelets or speckle reduction techniques, and the texture model may be better preserved in the AAM by decoupling from the shape model.

7.4.3 | Integration of presented techniques

Above all, previously presented techniques in this thesis should be integrated. At first, initialization of a model based approach might be improved using automated feature detection techniques as in chapter 5. Also, such a global segmentation technique may be extended with a spatially local refinement technique such as (multidimensional) dynamic programming, to relax the constraints from the statistical model, and improve matching to local image features. Single-phase detection using AAMs could be a basis for tracking approaches using for example MDP, providing the desired functional information such as ejection fraction, stroke volume etc., while avoiding complex 4D modeling.

7.5 | Conclusions

In conclusion, we have shown that we succeeded in developing methods that make analysis of 3D echocardiography more reliable and less user demanding. We improved on labour intensiveness and reliability of semi-automatic endocardial border detection. Automated tracking of the mitral valve can be done effectively, with high accuracy and precision in 2D echocardiography. Furthermore, we improved the general applicability of 3D echocardiography using the FRU transducer by achieving better reconstructions from the 3D+T data. This allowed us to develop methods that were not limited to data from the FRU transducer, but also applicable to data from commercially available matrix transducer systems. This led us to robust techniques for detection of the left ventricular long axis and the mitral valve plane. And finally, we showed the promise of fully automatic segmentation of the left ventricle using active appearance models.

The presented techniques may be of great value in related fields, such as reconstruction and analysis of transesophageal 3D echocardiography, freehand 3D echocardiography and 3D carotid imaging. Besides, advanced model-based segmentation using AAMs may benefit other modalities such as segmentation in cardiac MR and CT and may also improve from developments in those fields.

As discussed in the previous section, there are many opportunities to improve automated analysis of 3D echocardiography. Further development and integration of the presented techniques on reconstruction, feature detection, segmentation and tracking, and improvements in 3D ultrasound technology increasing the spatial and temporal resolution, may soon lead to reliable fully automatic solutions for left ventricular functional analysis based on our work.