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## Automated analysis of 3D echocardiography

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## Bibliography

- Achim, A., A. Bezerianos, and P. Tsakalides [2001]. Novel Bayesian multiscale method for speckle removal in medical ultrasound images. *IEEE T Med Imaging* 20;8: 772–83.
- Adam, D., S. Beilin-Nissan, Z. Friedman, and V. Behar [2006]. The combined effect of spatial compounding and nonlinear filtering on the speckle reduction in ultrasound images. *Ultrasonics* 44;2: 166–81.
- Alam, M. and C. Hoglund [1992]. Assessment by echocardiogram of left ventricular diastolic function in healthy subjects using the atrioventricular plane displacement. *Am J Cardiol* 69;5: 565–8.
- Amini, A., T. E. Weymouth, and R. C. Jain [1990]. Using dynamic programming for solving variational problems in vision. *IEEE T Pattern Anal* 12;9: 855–867.
- Angelini, E. D., A. F. Laine, S. Takuma, J. W. Holmes, and S. Homma [2001]. LV volume quantification via spatiotemporal analysis of real-time 3-D echocardiography. *IEEE T Med Imaging* 20;6: 457–69.
- Angelini, E. D., S. Homma, G. Pearson, J. W. Holmes, and A. F. Laine [2005]. Segmentation of real-time three-dimensional ultrasound for quantification of ventricular function: a clinical study on right and left ventricles. *Ultrasound Med Biol* 31;9: 1143–1158.
- Armstrong, W. F. and W. A. Zoghbi [2005]. Stress echocardiography: current methodology and clinical applications. *J Am Coll Cardiol* 45;11: 1739–47.
- Ballard, D. H. [1981]. Generalizing the Hough transform to detect arbitrary shapes. *Pattern Recogn* 13;2: 111–122.
- Barnett, S. B., G. R. Ter Haar, M. C. Ziskin, H. D. Rott, F. A. Duck, and K. Maeda [2000]. International recommendations and guidelines for the safe use of diagnostic ultrasound in medicine. *Ultrasound Med Biol* 26;3: 355–66.

- Barratt, D. C., A. H. Davies, A. D. Hughes, S. A. Thom, and K. N. Humphries [2001]. Optimisation and evaluation of an electromagnetic tracking device for high-accuracy three-dimensional ultrasound imaging of the carotid arteries. *Ultrasound Med Biol* 27;7; 957–968.
- Batur, A. U. and M. H. Hayes [2005]. Adaptive active appearance models. *IEEE T Image Process* 14;11; 1707–21.
- Bax, J. J., J. A. Patton, D. Poldermans, A. Elhendy, and M. P. Sandler [2000]. 18-Fluorodeoxyglucose imaging with positron emission tomography and single photon emission computed tomography: cardiac applications. *J Nucl Med* 30;4; 281–98.
- Behar, V., D. Adam, P. Lysyansky, and Z. Friedman [2004]. The combined effect of nonlinear filtration and window size on the accuracy of tissue displacement estimation using detected echo signals. *Ultrasonics* 41;9; 743–53.
- Beichel, R., G. Gotschuli, E. Sorantin, F. Leberl, and M. Sonka [2002]. Diaphragm dome surface segmentation in CT data sets: a 3D active appearance model approach. *Proc SPIE Med Imaging* 4684; 475–484.
- Beichel, R., H. Bischof, F. Leberl, and M. Sonka [2005]. Robust active appearance models and their application to medical image analysis. *IEEE T Med Imaging* 24;9; 1151–1169.
- Bellmann, R. E. [1965]. *Dynamic programming*. Princeton Univ Pr.
- Belohlavek, M., K. Tanabe, D. Jakrapanichakul, J. F. Breen, and J. B. Seward [2001]. Rapid three-dimensional echocardiography: clinically feasible alternative for precise and accurate measurement of left ventricular volumes. *Circulation* 103;24; 2882–4.
- Binder, T., M. Sussner, D. Moertl, T. Strohmer, H. Baumgartner, G. Maurer, and G. Porenta [1999]. Artificial neural networks and spatial temporal contour linking for automated endocardial contour detection on echocardiograms: a novel approach to determine left ventricular contractile function. *Ultrasound Med Biol* 25;7; 1069–76.
- Bland, J. M. and D. G. Altman [1986]. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1;8476; 307–10.
- Bohs, L. N. and G. E. Trahey [1991]. A novel method for angle independent ultrasonic imaging of blood flow and tissue motion. *IEEE T Bio-med Eng* 38;3; 280–6.
- Bosch, H. G., G. van Burken, F. Nijland, and J. H. C. Reiber [1998]. Overview of automated quantitation techniques in 2D echocardiography. In: *What's New in Cardiovascular Imaging*. Ed. by J. H. C. Reiber and E. E. van der Wall. Springer.
- Bosch, J. G. [2007]. Echocardiographic digital image processing and approaches to automated border detection. In: *The practice of clinical echocardiography*. Ed. by C. M. Otto. 3rd ed. Philadelphia: Saunders. 262–282.
-

- Bosch, J. G., S. C. Mitchell, B. P. F. Lelieveldt, M. Sonka, F. Nijland, and J. H. C. Reiber [2000]. Model-based automated border detection for quantitative stress echocardiography. *Eur Heart J* 21;Abstract suppl; 37.
- Bosch, J. G., S. C. Mitchell, B. P. F. Lelieveldt, F. Nijland, O. Kamp, M. Sonka, and J. H. C. Reiber [2002]. Automatic segmentation of echocardiographic sequences by active appearance motion models. *IEEE T Med Imaging* 21;11; 1374–1383.
- Broyden, C. G. [1965]. A class of methods for solving nonlinear simultaneous equations. *Math Comput* 19;92; 577–593.
- Bruining, N., C. T. Lancée, J. R. T. C. Roelandt, and N. Bom [2000]. Three-dimensional echocardiography paves the way toward virtual reality. *Ultrasound Med Biol* 26;7; 1065–1074.
- Canals, R., G. Lamarque, and P. Chatain [1999]. Volumetric ultrasound system for left ventricle motion imaging. *IEEE T Ultrason Ferr* 46;6; 1527–1538.
- Chen, E. J., W. K. Jenkins, and W. D. O'Brien Jr [1995]. Performance of ultrasonic speckle tracking in various tissues. *J Acoust Soc Am* 98;3; 1273–8.
- Christodoulou, C. I., C. S. Pattichis, M. Pantziaris, and A. Nicolaides [2003]. Texture-based classification of atherosclerotic carotid plaques. *IEEE T Med Imaging* 22;7; 902–12.
- Comaniciu, D., X. S. Zhou, and S. Krishnan [2004]. Robust real-time myocardial border tracking for echocardiography: an information fusion approach. *IEEE T Med Imaging* 23;7; 849–60.
- Cootes, T. F. and P. Kittipanya-ngam [2002]. Comparing variations on the active appearance model algorithm. *Proc Brit Mach Vis Conf*. 837–846.
- Cootes, T. F. and C. J. Taylor [2001a]. *Statistical models of appearance for computer vision*. [http://www.isbe.man.ac.uk/~bim/Models/app\\_model.ps.gz](http://www.isbe.man.ac.uk/~bim/Models/app_model.ps.gz).
- [2001b]. Statistical models of appearance for medical image analysis and computer vision. *Proc SPIE Med Imaging* 4322; 236–248.
- [2006]. An algorithm for tuning an active appearance model to new data. *Proc Brit Mach Vis Conf* 3; 919–928.
- Corbett, J. R. and E. P. Ficaro [1999]. Clinical review of attenuation-corrected cardiac SPECT. *J Nucl Cardiol* 6;1 Pt 1; 54–68.
- Corsi, C., G. Saracino, A. Sarti, and C. Lamberti [2002]. Left ventricular volume estimation for real-time three-dimensional echocardiography. *IEEE T Med Imaging* 21;9; 1202–1208.
- DeCara, J. M., E. Toledo, I. S. Salgo, G. Lammertin, L. Weinert, and R. M. Lang [2005]. Evaluation of left ventricular systolic function using automated angle-independent motion tracking of mitral annular displacement. *J Am Soc Echocardiog* 18;12; 1266–9.
- Dekker, D. L., R. L. Piziali, and E. Dong Jr [1974]. A system for ultrasonically imaging the human heart in three dimensions. *Comput Biomed Res* 7;6; 544–53.
-

- Delabays, A., N. G. Pandian, Q. L. Cao, L. Sugeng, G. Marx, A. Ludomirski, and S. L. Schwartz [1995]. Transthoracic real-time three-dimensional echocardiography using a fan-like scanning approach for data acquisition: methods, strengths, problems, and initial clinical experience. *Echocardiography* 12;1; 49–59.
- Djoa, K. K., N. de Jong, F. C. van Egmond, J. D. Kasprzak, W. B. Vletter, C. T. Lancee, A. F. W. van der Steen, N. Bom, and J. R. T. C. Roelandt [2000]. A fast rotating scanning unit for real-time three-dimensional echo data acquisition. *Ultrasound Med Biol* 26;5; 863–9.
- Drori, I., D. Cohen-Or, and H. Yeshurun [2003]. Fragment-based image completion. *ACM T Graphic* 22;3; 303–312.
- Duck, F. A. [2002]. Nonlinear acoustics in diagnostic ultrasound. *Ultrasound Med Biol* 28;1; 1–18.
- Engelse, W. A. H. and C. Zeelenberg [1979]. A single scan algorithm for QRS-detection and feature extraction. *Proc Comput Card* 6; 37–42.
- Estépar, R. S. J., M. Martín-Fernández, C. Alberola-López, J. Ellsmere, R. Kikinis, and C. F. Westin [2003]. Freehand ultrasound reconstruction based on ROI prior modeling and normalized convolution. *Lect Notes Comput Sc* 2879; 382–390.
- Eto, Y., H. Yamada, J. H. Shin, D. A. Agler, H. Tsujino, J. X. Qin, G. Saracino, N. L. Greenberg, J. D. Thomas, and T. Shiota [2005]. Automated mitral annular tracking: a novel method for evaluating mitral annular motion using two-dimensional echocardiography. *J Am Soc Echocardiog* 18;4; 306–12.
- Farsiu, S., D. Robinson, M. Elad, and P. Milanfar [2004]. Advances and challenges in super-resolution. *Int J Imag Syst Tech* 14;2; 47–57.
- Feigenbaum, H. [2004]. *Feigenbaum's echocardiography*. 6th ed. Philadelphia, PA: Lippincott Williams & Wilkins.
- Flachskampf, F. A., S. Chandra, A. Gaddipatti, R. A. Levine, A. E. Weyman, W. Ameling, P. Hanrath, and J. D. Thomas [2000]. Analysis of shape and motion of the mitral annulus in subjects with and without cardiomyopathy by echocardiographic 3-dimensional reconstruction. *J Am Soc Echocardiog* 13;4; 277–87.
- Frangi, A. F., W. J. Niessen, and M. A. Viergever [2001]. Three-dimensional modeling for functional analysis of cardiac images, a review. *IEEE T Med Imaging* 20;1; 2–25.
- Friedland, N. and D. Adam [1989]. Automatic ventricular cavity boundary detection from sequential ultrasound images using simulated annealing. *IEEE T Med Imaging* 8;4; 344–53.
- Funda, J. and R. P. Paul [1988]. A comparison of transforms and quaternions in robotics. *Proc IEEE Int Conf Robo Automat* 2; 886–891.
- Geleijnse, M. L., P. M. Fioretti, and J. R. T. C. Roelandt [1997]. Methodology, feasibility, safety and diagnostic accuracy of dobutamine stress echocardiography. *J Am Coll Cardiol* 30;3; 595–606.
-

- Gérard, O., A. C. Billon, J.-M. Rouet, M. Jacob, M. Fradkin, and C. Allouche [2002]. Efficient model-based quantification of left ventricular function in 3-D echocardiography. *IEEE T Med Imaging* 21;9: 1059–1068.
- Golemati, S., A. Sassano, M. J. Lever, A. A. Bharath, S. Dhanjil, and A. N. Nicolaides [2003]. Carotid artery wall motion estimated from B-mode ultrasound using region tracking and block matching. *Ultrasound Med Biol* 29;3: 387–99.
- Goodall, C. [1991]. Procrustes methods in the statistical analysis of shape. *J Roy Stat Soc B Met* 53;2: 285–339.
- Gower, J. C. [1975]. Generalized procrustes analysis. *Psychometrika* 40;1: 33–51.
- Gross, R., I. Matthews, and S. Baker [2006]. Active appearance models with occlusion. *Image Vision Comput* 24;6: 593–604.
- Hansegård, J., S. Urheim, K. Lunde, and S. I. Rabben [2007a]. Constrained active appearance models for segmentation of triplane echocardiograms. *IEEE T Med Imaging* 26;10: 1391–400.
- Hansegård, J., F. Orderud, and S. I. Rabben [2007b]. Real-time active shape models for segmentation of 3D cardiac ultrasound. *Lect Notes Comput Sc* 4673: 157–164.
- Horn, B. K. P. [1987]. Closed-form solution of absolute orientation using unit quaternions. *J Opt Soc Am* 4;4: 629–642.
- Jacob, G., J. A. Noble, C. Behrenbruch, A. D. Kelion, and A. P. Banning [2002]. A shape-space-based approach to tracking myocardial borders and quantifying regional left-ventricular function applied in echocardiography. *IEEE T Med Imaging* 21;3: 226–38.
- Jenkins, C., K. Bricknell, L. Hanekom, and T. H. Marwick [2004]. Reproducibility and accuracy of echocardiographic measurements of left ventricular parameters using real-time three-dimensional echocardiography. *J Am Coll Cardiol* 44;4: 878–86.
- Kaus, M. R., J. von Berg, J. Weese, W. J. Niessen, and V. Pekar [2004]. Automated segmentation of the left ventricle in cardiac MRI. *Med Image Anal* 8;3: 245–254.
- Knutsson, H. and C. F. Westin [1993]. Normalized and differential convolution. *Proc IEEE Int Conf Comput Vis Pattern Recogn.* 515–523.
- Kühl, H. P., M. Schreckenberg, D. Rulands, M. Katoh, W. Schafer, G. Schummers, A. Buckner, P. Hanrath, and A. Franke [2004]. High-resolution transthoracic real-time three-dimensional echocardiography: quantitation of cardiac volumes and function using semi-automatic border detection and comparison with cardiac magnetic resonance imaging. *J Am Coll Cardiol* 43;11: 2083–90.
- Larsen, R., M. B. Stegmann, S. Darkner, S. Forchhammer, T. F. Cootes, and B. Kjær Ersbøll [2007]. Texture enhanced appearance models. *Comput Vis Image Und* 106;1: 20–30.
-

- Leung, K. Y. E., R. A. Baldewising, F. Mastik, J. A. Schaar, A. Gisolf, and A. F. W. Van der Steen [2006*a*]. Motion compensation for intravascular ultrasound palpography. *IEEE T Ultrason Ferr* 53;7; 1269–1280.
- Leung, K. Y. E., M. van Stralen, G. van Burken, M. M. Voormolen, A. Nemes, F. J. ten Cate, N. de Jong, A. F. W. van der Steen, J. H. C. Reiber, and J. G. Bosch [2006*b*]. Sparse appearance model based registration of 3D ultrasound images. *Lect Notes Comput Sc* 4091; 236–243.
- Loke, R. E. and J. M. H. du Buf [2004]. Quadtree-guided 3-D interpolation of irregular sonar data sets. *IEEE J Oceanic Eng* 29;2; 457–471.
- Lorenz, C. H., E. S. Walker, V. L. Morgan, S. S. Klein, and Jr. Graham T. P. [1999]. Normal human right and left ventricular mass, systolic function, and gender differences by cine magnetic resonance imaging. *J Cardio Magn Reson* 1;1; 7–21.
- Mannaerts, H. E., J. A. van der Heide, O. Kamp, T. Papavassiliu, J. T. Marcus, A. Beek, A. C. van Rossum, J. Twisk, and C. A. Visser [2003]. Quantification of left ventricular volumes and ejection fraction using freehand transthoracic three-dimensional echocardiography: comparison with magnetic resonance imaging. *J Am Soc Echocardiog* 16;2; 101–9.
- Meairs, S., J. Beyer, and M. Hennerici [2000]. Reconstruction and visualization of irregularly sampled three- and four-dimensional ultrasound data for cerebrovascular applications. *Ultrasound Med Biol* 26;2; 263–72.
- Mignotte, M. and J. Meunier [2001]. A multiscale optimization approach for the dynamic contour-based boundary detection issue. *Comput Med Imag Grap* 25;3; 265–75.
- Mitchell, S. C., B. P. F. Lelieveldt, R. J. van der Geest, J. G. Bosch, J. H. C. Reiber, and M. Sonka [2001*a*]. Multistage hybrid active appearance model matching: segmentation of left and right ventricles in cardiac MR images. *IEEE T Med Imaging* 20;5; 415–423.
- [2001*b*]. Time continuous segmentation of cardiac MR image sequences using active appearance motion models. *Proc SPIE Med Imaging* 4322; 249–256.
- Mitchell, S. C., J. G. Bosch, B. P. F. Lelieveldt, R. J. van der Geest, J. H. C. Reiber, and M. Sonka [2002]. 3-D active appearance models: segmentation of cardiac MR and ultrasound images. *IEEE T Med Imaging* 21;9; 1167–1178.
- Mittrapiyanuruk, P., G. N. DeSouza, and A. C. Kak [2005]. Accurate 3D tracking of rigid objects with occlusion using active appearance models. *Proc IEEE Workshop Motion Vis Comput*.
- Montagnat, J. and H. Delingette [2000]. Space and time shape constrained deformable surfaces for 4D medical image segmentation. *Lect Notes Comput Sc* 1935; 687–696.
- Moritz, W. E. and P. L. Shreve [1976]. A microprocessor-based spatial-locating system for use with diagnostic ultrasound. *P IEEE* 64;6; 966–974.
-



- Müller, A., A. Neitmann, N. Merkle, J. Wöhrle, V. Hombach, and H. A. Kestler [2005]. Contour detection of short axis slice MR images for contraction irregularity assessment. *Proc Comput Card* 32; 21–24.
- Nijland, E., O. Kamp, P. M. Verhorst, W. G. de Voogt, H. G. Bosch, and C. A. Visser [2002]. Myocardial viability: impact on left ventricular dilatation after acute myocardial infarction. *Heart* 87;1; 17–22.
- Nillesen, M. M., R. G. Lopata, I. H. Gerrits, L. Kapusta, H. J. Huisman, J. M. Thijssen, and C. L. de Korte [2007]. Segmentation of the heart muscle in 3-D pediatric echocardiographic images. *Ultrasound Med Biol* 33;9; 1453–62.
- Nillesen, M. M., R. G. P. Lopata, I. H. Gerrits, L. Kapusta, J. M. Thijssen, and C. L. de Korte [2008]. Modeling envelope statistics of blood and myocardium for segmentation of echocardiographic images. *Ultrasound Med Biol* 34;4; 674–680.
- Noble, J. A. and D. Boukerroui [2006]. Ultrasound image segmentation: a survey. *IEEE T Med Imaging* 25;8; 987–1010.
- Nosir, Y. F., P. M. Fioretti, W. B. Vletter, E. Boersma, A. Salustri, J. T. Postma, A. E. Reijs, F. J. Ten Cate, and J. R. Roelandt [1996]. Accurate measurement of left ventricular ejection fraction by three-dimensional echocardiography. A comparison with radionuclide angiography. *Circulation* 94;3; 460–6.
- Nosir, Y. F., J. Stoker, J. D. Kasprzak, M. H. Lequin, A. Dall’Agata, F. J. Ten Cate, and J. R. Roelandt [1999]. Paraplane analysis from precordial three-dimensional echocardiographic data sets for rapid and accurate quantification of left ventricular volume and function: a comparison with magnetic resonance imaging. *Am Heart J* 137;1; 134–43.
- Oost, E., G. Koning, M. Sonka, P. V. Oemrawsingh, J. H. C. Reiber, and B. P. F. Lelieveldt [2006]. Automated contour detection in X-ray left ventricular angiograms using multiview active appearance models and dynamic programming. *IEEE T Med Imaging* 25;9; 1158–1171.
- Orderud, E., J. Hansgård, and S. I. Rabben [2007]. Real-time tracking of the left ventricle in 3D echocardiography using a state estimation approach. *Lect Notes Comput Sc* 4791; 858–865.
- Pai, R. G., M. M. Bodenheimer, S. M. Pai, J. H. Koss, and R. D. Adamick [1991]. Usefulness of systolic excursion of the mitral anulus as an index of left ventricular systolic function. *Am J Cardiol* 67;2; 222–4.
- Pandian, N. G., J. R. T. C. Roelandt, N. C. Nanda, L. Sugeng, Q. L. Cao, J. Azevedo, S. L. Schwartz, M. A. Vannan, A. Ludomirski, G. Marx, and M. Vogel [1994]. Dynamic three-dimensional echocardiography: methods and clinical potential. *Echocardiography* 11;3; 237–259.
- Papavassiliou, D., N. R. Doelling, M. K. Bowman, H. Yeung, J. Rock, B. Klas, K. Chung, and D. A. Fyfe [1998]. Initial experience with an internally rotating transthoracic
-

- three-dimensional echocardiographic probe and image acquisition on a conventional echocardiogram machine. *Echocardiography* 15;4; 369–376.
- Penney, G. P., J. A. Schnabel, D. Rueckert, M. A. Viergever, and W. J. Niessen [2004]. Registration-based interpolation. *IEEE T Med Imaging* 23;7; 922–6.
- Pham, T. Q. and L. J. van Vliet [2003]. Normalized averaging using adaptive applicability functions with applications in image reconstruction from sparsely and randomly sampled data. *Proc Scand Conf Image Anal.* 485–492.
- Raab, F. H., E. B. Blood, T. O. Steiner, and H. R. Jones [1979]. Magnetic position and orientation tracking system. *IEEE T Aero Elec Sys AES-15;5; 709–718.*
- Rabben, S. I., A. H. Torp, A. Støylen, S. Slørdahl, K. Bjørnstad, B. O. Haugen, and B. Angelsen [2000]. Semiautomatic contour detection in ultrasound M-mode images. *Ultrasound Med Biol* 26;2; 287–96.
- Roberts, M., T. F. Cootes, and J. E. Adams [2003]. Linking sequences of active appearance sub-models via constraints: an application in automated vertebral morphometry. *Proc Brit Mach Vis Conf* 1; 349–358.
- Roberts, M., T. F. Cootes, E. Pacheco, and J. E. Adams [2007]. Quantitative vertebral fracture detection on DXA images using shape and appearance models. *Acad Radiol* 14;10; 1166–1178.
- Sanchez-Ortiz, G. I., G. J. T. Wright, N. Clarke, J. Declerck, A. P. Banning, and J. A. Noble [2002]. Automated 3-D echocardiography analysis compared with manual delineations and SPECT MUGA. *IEEE T Med Imaging* 21;9; 1069–1076.
- Schuijf, J. D. and J. J. Bax [2008]. CT angiography: an alternative to nuclear perfusion imaging? *Heart* 94;3; 255–7.
- Schwartz, S. L., Q. L. Cao, J. Azevedo, and N. G. Pandian [1994]. Simulation of intraoperative visualization of cardiac structures and study of dynamic surgical anatomy with real-time three-dimensional echocardiography. *Am J Cardiol* 73;7; 501–507.
- Sivaramakrishna, R., K. A. Powell, M. L. Lieber, W. A. Chilcote, and R. Shekhar [2002]. Texture analysis of lesions in breast ultrasound images. *Comput Med Imag Grap* 26;5; 303–7.
- Smith, S. W., H. G. Pavy Jr, and O. T. von Ramm [1991]. High-speed ultrasound volumetric imaging system. I. Transducer design and beam steering. *IEEE T Ultrason Ferr* 38;2; 100–108.
- Sonka, M., V. Hlavac, and R. Boyle [1999]. *Image processing, analysis, and machine vision*. 2nd ed. Pacific Grove, CA: Brooks/Cole Publishing company.
- Spencer, K. T., J. Bednarz, P. G. Rafter, C. Korcarz, and R. M. Lang [1998]. Use of harmonic imaging without echocardiographic contrast to improve two-dimensional image quality. *Am J Cardiol* 82;6; 794–799.
-

- Stegmann, M. B. and D. Pedersen [2005]. Bi-temporal 3 D active appearance models with applications to unsupervised ejection fraction estimation. *Proc SPIE Med Imaging* 5747; 336–350.
- Stegmann, M. B., B. K. Ersboll, and R. Larsen [2003]. FAME—a flexible appearance modeling environment. *IEEE T Med Imaging* 22;10; 1319–31.
- Stegmann, M. B., H. Olafsdottir, and H. B. W. Larsson [2005]. Unsupervised motion-compensation of multi-slice cardiac perfusion MRI. *Med Image Anal* 9;4; 394–410.
- Stetten, G. D. and S. M. Pizer [1999]. Medial-node models to identify and measure objects in real-time 3-D echocardiography. *IEEE T Med Imaging* 18;10; 1025–1034.
- Tauber, C., H. Batatia, and A. Ayache [2004]. A robust speckle reducing anisotropic diffusion. *Proc Int Conf Image Process* 1; 247–250.
- Thodberg, H. H. [2002]. Hands-on experience with active appearance models. *Proc SPIE Med Imaging* 4684; 495–506.
- Thomas, J. D. and D. N. Rubin [1998]. Tissue harmonic imaging: why does it work? *J Am Soc Echocardiog* 11;8; 803–808.
- Tranquart, F., N. Grenier, V. Eder, and L. Pourcelot [1999]. Clinical use of ultrasound tissue harmonic imaging. *Ultrasound Med Biol* 25;6; 889–894.
- Unser, M., G. Pelle, P. Brun, and M. Eden [1989]. Automated extraction of serial myocardial borders from M-mode echocardiograms. *IEEE T Med Imaging* 8;1; 96–103.
- Üzümcü, M., R. J. van der Geest, M. Sonka, H. J. Lamb, J. H. C. Reiber, and B. P. F. Lelieveldt [2005]. Multiview active appearance models for simultaneous segmentation of cardiac 2- and 4-chamber long-axis magnetic resonance images. *Invest Radiol* 40;4; 195–203.
- Üzümcü, M., R. J. van der Geest, C. Swingen, J. H. C. Reiber, and B. P. F. Lelieveldt [2006]. Time continuous tracking and segmentation of cardiovascular magnetic resonance images using multidimensional dynamic programming. *Invest Radiol* 41;1; 52–62.
- Van der Geest, R. J., V. G. Buller, E. Jansen, H. J. Lamb, L. H. Baur, E. E. van der Wall, A. de Roos, and J. H. Reiber [1997]. Comparison between manual and semiautomated analysis of left ventricular volume parameters from short-axis MR images. *J Comput Assist Tomo* 21;5; 756–65.
- Van Stralen, M., J. G. Bosch, M. M. Voormolen, G. van Burken, B. J. Krenning, R. M. van Geuns, C. T. Lancée, N. de Jong, and J. H. C. Reiber [2005]. Left ventricular volume estimation in cardiac three-dimensional ultrasound: a semiautomatic border detection approach. *Acad Radiol* 12;10; 1241–1249.
- Varandas, J., P. Baptista, J. Santos, R. Martins, and J. Dias [2004]. VOLUS—a visualization system for 3D ultrasound data. *Ultrasonics* 42;1-9; 689–694.
-

- Veronesi, F., C. Corsi, E. G. Caiani, A. Sarti, and C. Lamberti [2006]. Tracking of left ventricular long axis from real-time three-dimensional echocardiography using optical flow techniques. *IEEE T Inf Technol B* 10;1; 174–81.
- Von Ramm, O. T., S. W. Smith, and H. G. Pavy Jr [1991]. High-speed ultrasound volumetric imaging system. II. Parallel processing and image display. *IEEE T Ultrason Ferr* 38;2; 109–115.
- Vormolen, M. M. and M. G. Danilouchkine [2007]. Aspects of left ventricular volume comparison between 3D echocardiography and MRI. *J Am Soc Echocardiog* 20;12; 1421–1422.
- Vormolen, M. M., A. Bouakaz, B. J. Krenning, C. T. Lancée, F. J. ten Cate, J. R. T. C. Roelandt, A. F. van der Steen, and N. de Jong [2002]. A new transducer for 3D harmonic imaging. *Proc IEEE Int Ultrason Symp.* 1261–1264.
- Vormolen, M. M., B. J. Krenning, C. T. Lancée, F. J. ten Cate, J. R. T. C. Roelandt, A. F. W. van der Steen, and N. de Jong [2003]. Quantitative harmonic 3D echocardiography with a fast rotating ultrasound transducer. *Proc IEEE Int Ultrason Symp.* 122–125.
- Vormolen, M. M., B. J. Krenning, C. T. Lancée, F. J. ten Cate, J. R. Roelandt, A. F. van der Steen, and N. de Jong [2006]. Harmonic 3-D echocardiography with a fast-rotating ultrasound transducer. *IEEE T Ultrason Ferr* 53;10; 1739–48.
- Vormolen, M. M., B. J. Krenning, R. J. van Geuns, J. Borsboom, C. T. Lancée, F. J. ten Cate, J. R. T. C. Roelandt, A. F. van der Steen, and N. de Jong [2007]. Efficient quantification of the left ventricular volume using 3-dimensional echocardiography: the minimal number of equiangular long-axis images for accurate quantification of the left ventricular volume. *J Am Soc Echocardiog* 20;4; 373–80.
- WHO, World Health Organisation [2007]. Fact sheet N<sup>o</sup> 317: Cardiovascular disease. <http://www.who.int/mediacentre/factsheets/fs317/en/index.html>.
- Ward, B., A. C. Baker, and V. F. Humphrey [1997]. Nonlinear propagation applied to the improvement of resolution in diagnostic medical ultrasound. *J Acoust Soc Am* 101;1; 143–154.
- Wells, P. N. T. and M. Halliwell [1981]. Speckle in ultrasonic imaging. *Ultrasonics* 19;5; 225–229.
- Westin, C. F. [1994]. A tensor framework for multidimensional signal processing. PhD thesis. Linköping University.
- Willenheimer, R., B. Israelsson, C. Cline, E. Rydberg, K. Broms, and L. Erhardt [1999]. Left atrioventricular plane displacement is related to both systolic and diastolic left ventricular performance in patients with chronic heart failure. *Eur Heart J* 20;8; 612–8.
- Williams, B. R. [1994]. A retrospective study of the diagnostic accuracy of a community hospital-based PET center for the detection of coronary artery disease using rubidium-82. *J Nucl Med* 35;10; 1586–1592.
-

- Xiao, C.-Y., S. Zhang, and Y.-Z. Chen [2004]. A diffusion stick method for speckle suppression in ultrasonic images. *Pattern Recogn Lett* 25;16; 1866–1876.
- Xie, J., Y. Jiang, and H. T. Tsui [2005]. Segmentation of kidney from ultrasound images based on texture and shape priors. *IEEE T Med Imaging* 24;1; 45–57.
- Xu, C. X. [1990]. Hybrid method for nonlinear least-square problems without calculating derivatives. *J Optimiz Theory App* 65;3; 555–574.
- Yoshida, H., D. D. Casalino, B. Keserci, A. Coskun, O. Ozturk, and A. Savranlar [2003]. Wavelet-packet-based texture analysis for differentiation between benign and malignant liver tumours in ultrasound images. *Phys Med Biol* 48;22; 3735–53.
- Yu, Y. and S. T. Acton [2002]. Speckle reducing anisotropic diffusion. *IEEE T Image Process* 11;11; 1260–1270.
- Zagrodsky, V., V. Walimbe, C. R. Castro-Pareja, J. X. Qin, J. M. Song, and R. Shekhar [2005]. Registration-assisted segmentation of real-time 3-D echocardiographic data using deformable models. *IEEE T Med Imaging* 24;9; 1089–99.
- Zheng, Y., A. Barbu, B. Georgescu, M. Scheuering, and D. Comaniciu [2007]. Fast automatic heart chamber segmentation from 3D CT data using marginal space learning and steerable features. *Proc IEEE Int Conf Comput Vis.* 1–8.
- Zhou, X. S., D. Comaniciu, and A. Gupta [2005]. An information fusion framework for robust shape tracking. *IEEE T Pattern Anal* 27;1; 115–29.
- Zhu, Y., X. Papademetris, A. Sinusas, and J. S. Duncan [2007]. Segmentation of myocardial volumes from real-time 3D echocardiography using an incompressibility constraint? *Lect Notes Comput Sc* 4791; 44–51.
-



# Publications

## Journal papers

- Leung, K. Y. E., **M. van Stralen**, A. Nemes, M. M. Voormolen, G. van Burken, M. L. Geleijnse, F. J. Ten Cate, J. H. C. Reiber, N. de Jong, A. F. W. van der Steen, and J. G. Bosch [2008]. Sparse registration for three-dimensional stress echocardiography. *IEEE T Med Imaging* 27;11; 1568–79.
- Nemes, A., K. Y. E. Leung, G. van Burken, **M. van Stralen**, J. G. Bosch, O. I. Soliman, B. J. Krenning, W. B. Vletter, F. J. Cate, and M. L. Geleijnse [2008, in press]. Side-by-side viewing of anatomically aligned left ventricular segments in three-dimensional stress echocardiography. *Echocardiography*.
- Nevo, S. T., **M. van Stralen**, A. M. Vossepoel, J. H. Reiber, N. de Jong, A. F. W. van der Steen, and J. G. Bosch [2007]. Automated tracking of the mitral valve annulus motion in apical echocardiographic images using multidimensional dynamic programming. *Ultrasound Med Biol* 33;9; 1389–99.
- van Stralen, M.**, J. G. Bosch, M. M. Voormolen, G. van Burken, B. J. Krenning, R. M. van Geuns, C. T. Lancée, N. de Jong, and J. H. C. Reiber [2005]. Left ventricular volume estimation in cardiac three-dimensional ultrasound: a semiautomatic border detection approach. *Acad Radiol* 12;10; 1241–1249.
- van Stralen, M.**, K. Y. Leung, M. M. Voormolen, N. de Jong, A. F. W. van der Steen, J. H. C. Reiber, and J. G. Bosch [2008]. Time continuous detection of the left ventricular long axis and the mitral valve plane in 3-D echocardiography. *Ultrasound Med Biol* 34;2; 196–207.

## | Peer-reviewed conference proceeding papers

Leung, K. Y. E., **M. van Stralen**, G. van Burken, M. M. Voormolen, A. Nemes, F. J. ten Cate, N. de Jong, A. F. W. van der Steen, J. H. C. Reiber, and J. G. Bosch [2006]. Sparse appearance model based registration of 3D ultrasound images. Proc Med Imaging Augmented Reality Lect Notes Comput Sc 4091; 236–243.

**van Stralen, M.**, J. G. Bosch, M. M. Voormolen, G. van Burken, B. J. Krenning, C. T. Lancée, N. de Jong, and J. H. C. Reiber [2004]. A semi-automatic endocardial border detection method for the left ventricle in 4D ultrasound data sets. Proc Medical Image Computing and Computer Assisted Intervention Lect Notes Comput Sc 3216; 43–50.

## | Other conference proceeding papers

Bosch, J. G., **M. van Stralen**, M. M. Voormolen, B. J. Krenning, C. T. Lancée, J. H. C. Reiber, A. F. W. van der Steen, and N. de Jong [2005]. Improved spatiotemporal voxel space interpolation for 3D echocardiography with irregular sampling and multibeam fusion. Proc IEEE Int Ultrason Symp 2;

— [2006]. Novel spatiotemporal voxel interpolation with multibeam fusion for 3D echocardiography with irregular data distribution. Proc SPIE Med Imaging 6147; 61470Q.

Leung, K. Y. E., **M. van Stralen**, M. M. Voormolen, G. van Burken, A. Nemes, F. J. ten Cate, M. L. Geleijnse, N. de Jong, A. F. W. van der Steen, J. H. C. Reiber, and J. G. Bosch [2006a]. Registration of 2D cardiac images to real-time 3D ultrasound volumes for 3D stress echocardiography. Proc SPIE Med Imaging 6144; 614418.

Leung, K. Y. E., **M. van Stralen**, G. van Burken, M. M. Voormolen, A. Nemes, F. J. ten Cate, M. L. Geleijnse, N. de Jong, A. F. W. van der Steen, J. H. C. Reiber, and J. G. Bosch [2006b]. Sparse appearance model based registration and segmentation of 3D echocardiographic images. Proc IEEE Int Ultrason Symp. 2413–2416.

Leung, K. Y. E., **M. van Stralen**, M. M. Voormolen, N. de Jong, A. F. W. van der Steen, J. H. C. Reiber, and J. G. Bosch [2008]. Improving 3D active appearance model segmentation of the left ventricle with Jacobian tuning. Proc SPIE Med Imaging 6914; 69143B.

---



- Nathanail, K., **M. van Stralen**, C. Prins, F. van den Adel, P. J. French, N. de Jong, A. F. W. van der Steen, and J. G. Bosch [2008, in press]. Rapid 3D transesophageal echocardiography using a fast rotating multiplane transducer. Proc IEEE Int Ultrason Symp.
- van Stralen, M.**, J. G. Bosch, M. M. Voormolen, G. van Burken, B. J. Krenning, C. T. Lancée, N. de Jong, and J. H. C. Reiber [2004]. A semi-automatic endocardial border detection method for the left ventricle in 4D ultrasound data sets. Proc Computer Assisted Radiology and Surgery Int Congress Series 1268; 1078–1083.
- van Stralen, M.**, M. M. Voormolen, G. van Burken, B. J. Krenning, R. J. M. van Geuns, E. Angelié, R. J. van der Geest, C. T. Lancée, N. de Jong, A. F. W. van der Steen, J. H. C. Reiber, and J. G. Bosch [2005a]. A novel dynamic programming based semi-automatic endocardial border detection method for 4D cardiac ultrasound. Proc IEEE Int Ultrason Symp. 1232–1235.
- van Stralen, M.**, J. G. Bosch, M. M. Voormolen, G. van Burken, B. J. Krenning, R. J. M. van Geuns, E. Angelié, R. J. van der Geest, C. T. Lancée, N. de Jong, and J. H. C. Reiber [2005c]. Semi-automatic border detection method for left ventricular volume estimation in 4D ultrasound data. Proc ASCI Conf. 200–207.
- van Stralen, M.**, J. G. Bosch, M. M. Voormolen, G. van Burken, B. J. Krenning, R. J. M. van Geuns, E. Angelié, R. J. van der Geest, C. T. Lancée, N. de Jong, and J. H. C. Reiber [2005b]. Semi-automatic border detection method for left ventricular volume estimation in 4D ultrasound data. Proc SPIE Med Imaging 5747; 1457–1467.
- van Stralen, M.**, K. Y. E. Leung, M. M. Voormolen, N. de Jong, A. F. W. van der Steen, J. H. C. Reiber, and J. G. Bosch [2007a]. Automatic segmentation of the left ventricle in 3D echocardiography using active appearance models. Proc IEEE Int Ultrason Symp. 1480–1483.
- [2007b]. Fully automatic detection of the left ventricular long axis and mitral valve plane in 3D echocardiography. Proc IEEE Int Ultrason Symp. 2413–2416.
-

## | Submitted papers

Leung, K. Y. E., **M. van Stralen**, M. G. Danilouchkine, N. de Jong, A. F. W. van der Steen, and J. G. Bosch [2008, submitted]. Motion-guided optical flow tracking for segmenting 4D echocardiograms. *IEEE T Med Imaging*.

Ma, M., **M. van Stralen**, J. H. C. Reiber, J. G. Bosch, and B. P. F. Lelieveldt [2008, submitted]. Model driven quantification of left ventricular function from sparse single-beat 3D echocardiography. *IEEE T Med Imaging*.

## | Abstracts

Bosch, J. G., **M. van Stralen**, K. Y. E. Leung, M. M. Voormolen, N. de Jong, and A. F. W. van der Steen [2007]. Quantification of left ventricular volume and endocardial wall motion in real-time 3D echocardiography. *Proc First Dutch Conf on Bio-Medical Engineering*. 140.

Leung, K. Y. E., A. Nemes, G. van Burken, **M. van Stralen**, J. G. Bosch, O. I. Soliman, F. J. ten Cate, and M. L. Geleijnse [2008]. Improving interobserver agreement of three-dimensional stress echocardiography using novel side-by-side viewing software. *Eur J Echocardiog* 9;S1; S160.

Nemes, A., K. Y. E. Leung, G. van Burken, **M. van Stralen**, J. G. Bosch, O. I. I. Soliman, B. J. Krenning, W. B. Vletter, F. J. ten Cate, and M. L. Geleijnse [2008]. Side-by-side viewing of anatomically aligned left ventricular segments in three-dimensional stress echocardiography. *Eur Heart J* 29;S1;

Nevo, S. T., **M. van Stralen**, A. M. Vossepoel, J. H. Reiber, N. de Jong, A. F. W. van der Steen, and J. G. Bosch [2006]. Automated tracking of the mitral valve ring motion in apical echocardiographic images. *Eur J Echocardiog* 7;S1; S120.

**van Stralen, M.**, J. G. Bosch, M. M. Voormolen, G. van Burken, B. J. Krenning, R. J. M. van Geuns, C. T. Lancée, N. de Jong, and J. H. C. Reiber [2004]. Semi-automatic left ventricular endocardial border detection method for 4D ultrasound data. *Eur J Echocardiog* 5;S1; S57.

**van Stralen, M.**, J. G. Bosch, M. M. Voormolen, G. van Burken, B. J. Krenning, R. J. M. van Geuns, E. Angelié, R. J. van der Geest, C. T. Lancée, N. de Jong, and J.

---

H. C. Reiber [2005]. Evaluation of automated full cycle left ventricular volume estimation for real-time 3D echo against MRI. *Eur J Echocardiog* 6;S1; S131.

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Marijn van Stralen  
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## Curriculum Vitae



Marijn van Stralen was born in Roermond, the Netherlands, on March 15, 1980. He obtained his VWO degree at the Stedelijk Lyceum in Roermond in 1998. In 2003, he earned his Master's Degree in Medical-Technical Computer Science at Utrecht University, by completing his internship at TNO Human Factors in Soesterberg, on analysis of 3D meshes generated by 3D human body scanners.

He started his professional career as a PhD student on automated analysis of 3D echocardiography in 2003. At first in Leiden at the Laboratory for Clinical and Experimental Image Processing (LKEB) at the Leiden University Medical Center and from 2005 at the department of Biomedical Engineering (Thoraxcenter) at the Erasmus Medical Center in Rotterdam, the Netherlands. The results of his research on this subject are summarized in this thesis.

Since 2008, he has taken a position as post-doc researcher on multimodal image registration and segmentation, primarily of pre- and intra-operative brain images at the Image Sciences Institute at the University Medical Center in Utrecht, the Netherlands.

