Imaging of Transverse Cross Section of Carotid Artery Using Diverging Transmit Beams from Linear Array Ultrasonic Transducer with Multiple Steered Receive Beamforming

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学位論文題目	Imaging of Transverse Cross Section of Carotid Artery Using Diverging Transmit Beams from Linear Array Ultrasonic Transducer with Multiple Steered Receive Beamforming (超音波アレイトランスジューサを用いた拡散ビーム送信と多数の受信偏向ビームによる頸動脈短軸断面のイメージング)
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論 文 内 容 要 旨

One of the main causes of cardiovascular diseases is atherosclerosis and it strongly correlates with carotid arterial wall thickening of the intima-media complex. A typical arterial wall consists of three layers: an innermost layer, "the intima"; a middle layer, "the media"; and an outer layer, "the adventitia". The intima-media region of the artery is a useful place to probe in the diagnosis of atherosclerosis. Ultrasound imaging has been a very useful, safe and non-invasive imaging modality for visualizing the cross section of the arterial wall. Cross sectional imaging of the carotid artery is usually in two planes: the longitudinal plane and the transverse plane. In a longitudinal cross sectional image obtained by conventional linear scanning, the anterior and posterior walls are clearly displayed as double line pattern which represents echoes from the lumen-intima and media-adventitia boundaries. However in transverse cross sectional imaging, the intima-media complex of the carotid arterial wall is difficult to image using conventional linear scanning because reflection of ultrasound is highly angle-dependent, and in such scanning, the arterial wall is perpendicular to the direction of the ultrasonic beams in a limited region. This causes the extent of the arterial wall that is clearly imaged to be very limited. Ultrasound intravascular imaging modality which can be used to image the transverse cross section is invasive, expensive and can only be applied to patients that have already undergone surgical operation.

For this research, a parameter is introduced which is termed the *angular width* of the imaged region of the intima-media complex of the arterial wall. This parameter as used in this thesis, is a measure of the extent of the anterior and posterior intima-media walls of the arterial cross section that are clearly imaged, if the transverse cross section of the arterial lumen is assumed to be circular. For circular structures such as tube phantom, the angular width is a measure of the extent of the anterior and posterior walls of the tube's cross section that are clearly imaged.

The primary aim of this thesis is to obtain a wider angular width of imaged region of transverse cross section of the carotid artery than that is obtainable using conventional linear scanning. In this research, the use of multi element diverging beam from a linear array transducer with parallel steered receive beamforming and scanning in a linear sequential fashion was proposed. B-mode image was re-constructed from combinations of many steered receiving beams from multiple transmissions per frame. This method is expected to obtain a wider angular width of imaged region in carotid artery imaging. Since the transmitted beams are wide, there is more stringent requirement on the receive beamformer to be less sensitive to receive grating lobes. A method of modulating the receiving beams was introduced to further suppress grating lobe artifacts. This thesis is a report of the research that was carried out and it is divided into six chapters.

Chapter 1 describes the problem, motivation, objectives and the proposed method. Also, some fundamentals relating to ultrasound imaging, carotid arterial wall and other imaging approaches by other researchers are described.

Chapter 2 gives a detailed description of the principle of the proposed method. Generation of multi element diverging beam; creation of steered receiving beams and spatial combination of steered receiving beams from multiple transmissions are described. Receive steering angle is limited to $\pm 65^{\circ}$ with angular separation of 0.5°. This value of angular separation corresponds to the angle of first nulls with respect to the peak of the main lobe at steering angle of 0°, of overall array directivity for an array with inter-element distance of 0.2 mm at a frequency of 10 MHz. The linear array transducer used in experiments has these specifications.

Parameters to consider for achieving maximum possible angular width of imaged region are described. Also, because the transmit beam is wide, strong reception is possible from the direction of the receive-main lobe as well as directions of receive-grating lobes leading to grating lobe artifacts. Therefore, a method of modulation of the receiving beams in order to suppress grating lobe artifacts without loss in spatial resolution of reconstructed B-mode images is proposed and described.

In Chapter 3, acoustic field characteristics of the transmit beam from linear array transducer was investigated by simulation, for beams of various beam-spread angles ranging from 0° to 180°. Beam-spread angle of 0° corresponds to a plane wave. The simulated emitted acoustic waveform was found to be a composite of two components which in this thesis are referred to as 'main pulses' and the 'trailing pulses'. The main pulses are effective for imaging, but the trailing pulses cause depth sidelobe and range ambiguity artifacts in B-mode images. It also affects the image contrast. The trailing pulses depends on the beam parameters especially the aperture length, inter-element pitch and the beam-spread angle. As the beam-spread angle increases, the absolute amplitude of the main pulses is reducing while those of the trailing pulses are increasing. The spatial and temporal length, as well as the amplitude of the trailing pulses, varies for different locations within the beam. Simulation shows that the average amplitude of the trailing pulses is lower to that of the main pulses for beam-spread angles up to 120°.

Moreover, a 2-interface cylindrical tube composed of point scatterers of inter-scatterer distance of 20 μm (outer wall diameter of 10 mm and inner wall diameter of 8 mm) was simulated and virtual scanning in the transverse plane, using conventional linear scanning and the proposed scheme with a 192-element linear array transducer, were performed for various beam-spread angles and sub apertures sizes of 36, 56 and 96 elements. The center of the tube's cross section is positioned at a depth of 14.1 mm. The maximum value of observable angular width of 85° with beam-spread angle of 87° and transmit sub aperture size of 36 elements was obtained from simulations. Also, simulations showed that the observable angular width reduces with increasing depth of center of tube's cross section. The proposed method of suppression of grating lobe artifacts by modulation of receiving beams was applied to reconstructed B-mode image obtained from simulation of virtual scanning of columns of point scatterers in water and a grating lobe artifact suppression of about 40 dB was realized.

The result obtained in Chapter 3 was validated by phantom experiments in Chapter 4. A silicone-rubber tube phantom in water was scanned using conventional linear scanning and the proposed method described in Chapter 2 for beams with beam-spread angles ranging from 87° to 150°; and sub apertures sizes of 36, 56 and 96 elements. Maximum angular width of 60° with beam-spread angle of 87° and transmit sub aperture size of 36 elements was obtained from diverging beam scanning as opposed to 24° obtained from conventional linear scanning. This is an increase of about 2.5. A beam-spread angle of 90° with transmit sub aperture size of 36 elements were selected for *in vivo* imaging. Also, the proposed method of modulation of receiving beams, when applied to the phantom B-mode image, suppresses grating lobe artifacts without loss in spatial resolution.

The receive signal characteristics with wall orientation and scatterers' distribution were investigated for different regions of the walls (anterior/posterior walls and the side walls). This was performed by simulations of different scatterers' distribution and use of the phantom data. The work reveals that the receive signals (due to constructive and destructive interference) depends highly on (apart from transducer's transmit/receive directivity) orientation of the walls interface with respect to the direction of propagation of the transmit wavefronts/receiving beams' direction (which produces "edge effects"), and scatterers' strength and distribution (regular or random) within the walls with respect to the wavelength. The edge effect is angle dependent and is at play in the anterior and posterior walls of the tube. However, for regions filled with point scatterers, the receive signal strength is low due to scattering, not angle dependent but depends on the scatterer's distribution in relation to the wavelength. This is responsible for speckle observed in ultrasound imaging.

In this study, it is also found that at every point within the walls of the tube, the received signals of the steered receiving beams of different transmissions are not always coherent which causes partial cancellation effect for the combined signals from multiple transmissions due to randomness of the scatterers' scattering amplitude and inter spacing in relation to the wavelength. If the spacing is less than half a wavelength and regular for all scatterers, total cancellation effect will occur. This phenomenon is found to be at play in the imaging of the sidewalls because the orientation of the edge of the side walls is not normal to the direction of propagation of the transmit wavefronts/direction of the steered receiving beams of most of the transmissions. Also, large difference in speed of ultrasound between the material of the silicone-rubber tube phantom and water (which is assumed same in the imaging) is also responsible.

Having selected the use of beam spread angle of 90° and sub aperture size of 36 elements from the previous chapters, carotid artery imaging was performed in transverse plane on three adult male human subjects. This is described in Chapter 5. The average result obtained for the angular width from diverging beam scanning is about 45° and 24° from conventional linear scanning; yielding a ratio of about 1.9. Application of the proposed method of modulation of receiving beams to the *in vivo* images, suppresses grating lobe artifacts without loss in spatial resolution.

Chapter 6 concludes the thesis, indicates some processing times for some operations with two different versions of MATLAB software (Version 6.1.0.450 Release 12.1, May 18, 2001 and Version 7.8.0.347 Release 2009a, February 12, 2009) on two different operating system software (Windows XP and Windows Vista respectively) and hardware (Dell and Hewlett-Packard) platforms. The processing times are longer with the older version of MATLAB software than the newer version. Chapter 6 also highlights some contributions and makes some suggestions for future investigations.

論文審査結果の要旨

超音波による頸動脈壁内膜中膜複合体(intima-media complex: IMC)の厚み(intima-media thickness: IMT)測定は，非侵襲で繰り返し測定が可能な動脈硬化診断手法として広く普及している．しかし，超音波反射には強い角度依存性があるため，超音波ビームと動脈壁とのなす角が 90 度付近でないと超音波断層像において IMC が明瞭に描出されない．従来の超音波走査法(リニア走査)におけるビーム方向は 1 方向のみであるため，特に動脈の短軸(輪切り)断面においてはごく狭い領域しか超音波ビームと動脈壁が直交しないという問題があった．著者は，扇状に拡散する超音波を照射し，その照射範囲内の各点に対して多数の角度で超音波ビームを形成することにより，頸動脈短軸断面の描出能を向上させる手法について研究を行った．本論文はこれらの成果をまとめたもので，全編 6 章よりなる．

第 1 章は序論である．

第 2 章では，著者が新たに開発した超音波イメージング法における，超音波アレイトランスジューサ内に想定した仮想点音源からある角度(拡散角度)で扇状に拡散する超音波ビームを送信する方法，受信集束超音波ビームを多数の偏向角度で形成し，複数送信回の受信ビームを重ね合わせて超音波断層像を構築する方法，さらに受信ビームを変調してグレーティングローブを低減させる方法について述べている．

第 3 章では，計算機シミュレーションにより送信および受信ビーム形成における最適条件を検討している．送信ビームの拡散角度が大きいほど偏向角度の大きい受信ビームを形成でき，ビームと動脈壁を直交させやすい．一方，総送信エネルギーは一定であるため，トランスジューサ各素子から送信される超音波の位相が整合して形成される波面が広く(拡散角度が大きく)なると音圧(超音波振幅)は低下する．また，位相不整合により発生する不要成分も増加することが確認された．典型的な条件である超音波周波数 10 MHz，素子数 192 (間隔 0.2 mm)について検討したところ，不要成分を波面の超音波振幅以下に抑えるためには拡散角度を 120 度以下に抑える必要があり，その条件下で円筒管の描出範囲が最大となるのは拡散角度 90 度であることを明らかにした．また，素子の指向性から，偏向角度±65 度まで受信集束ビームを形成可能であることを示した．さらに，受信信号中のグレーティングローブを発生しない低周波成分の振幅により受信ビームに重みを付けることにより，虚像を 40 dB 低減できることを示した．

第 4 章では，模擬血管を用いた評価実験について述べている．超音波アレイトランスジューサ各素子への印加信号の遅延時間を制御可能な超音波診断装置を用いて，第 2 章において最適化した送信条件を実現した．提案手法を用いて模擬血管の短軸断面像を計測したところ，模擬血管壁の描出範囲は，模擬血管短軸中心に対する角度範囲として 60 度であり，従来法の 24 度に対し 2.5 倍とより広範囲で描出でき実用上極めて有用である．

第 5 章では，ヒト頸動脈の測定について述べている．第 4 章と同様に，第 2 章で最適化した送信条件を用いて実験を行い，ヒト頸動脈短軸断面を計測した．その結果，頸動脈壁の描出範囲は 45 度であり，従来法の 24 度に対して 1.9 倍であった．これは減衰が大きくかつ音速分布が不均一である生体組織においても，本手法が有効であることを示す重要な知見である．

第 6 章は結論である．

以上要するに本論文は，超音波送信・受信音場を制御することにより超音波イメージングにおいて角度依存性の大きい対象物も描出可能であることを理論的に示すとともに，その有用性を実証する結果を実験的に得たものであり，医用超音波工学および電子工学の発展に寄与するところが少なくない．

よって，本論文は博士(工学)の学位論文として合格と認める．