Contactless Carotid Pulse Measurement Using Continuous Wave Radar

Kilin Shi*, Sven Schellenberger†, Tobias Steigleder‡, Fabian Michler*, Fabian Lurz*,
Robert Weigel* and Alexander Koelpin†

* *Institute for Electronics Engineering, Friedrich-Alexander University Erlangen-Nuremberg, 91058 Erlangen, Germany*
kilin.shi@fau.de
† *Chair for Electronics and Sensor Systems, Brandenburg University of Technology, 03046 Cottbus, Germany*
‡ *Department of Palliative Care and Department of Neurology, Universitätsklinikum Erlangen, 91054 Erlangen, Germany*

***Abstract*—Cardiovascular diseases are one of the major causes of death. Regular checkups and preventive actions can drastically help reducing fatal incidences. This can be achieved by monitoring the carotid artery or rather the carotid pulse signal. Commonly, ultrasound devices are used for that purpose. However, these devices are costly, mostly stationary and their usage requires training and experience. This paper investigates the possible usage of radar systems as a contactless and low-cost alternative for carotid pulse measurements. Theoretical investigations reveal a linear relationship between the measurands of both devices and synchronous recordings from three test persons further confirm the feasibility of using radar systems as a potential device for monitoring cardiovascular diseases.**

***Index Terms*—biomedical monitoring, biomedical signal analysis, cardiovascular system, cw radar, medical sensors, radar signal analysis, ultrasound**

I. Introduction

The carotid artery provides large areas of the brain with blood. Its clinical evaluation is of great diagnostic importance. It is susceptible to metabolic challenges, e.g., elevated blood pressure and glucose levels [1]. In vascular diseases its cross section narrows gradually, leading to deprivation of oxygen and stroke. Also specific changes of the structure of the vessel wall occur, which herald vascular diseases elsewhere in the body and correlate highly with occurrence of myocardial infarction [2]. Regular screening for stenosis and remodelling of the vessel wall identifies patients at risk and facilitates prophylactic measures in order to maintain health. If changes proceed unchecked, stroke and myocardial infarction may occur: the most common causes for death as well as disability [3] and increasingly high economic burden in health care [4]. Changes of cross section as well as its impact on dynamics of blood flow and structural changes of the carotid wall can be detected by ultrasound examination of the carotid artery [5]. Whereas individuals at risk profit from regular examinations [6], implementation is restricted by limited human resources and constricted access to technology. Ultrasound devices are costly and mostly stationary. Operating ultrasound devices requires training and experience. To bridge the gap between demand and support, a device to identify pathological changes of carotid vessels is necessary, which is easily transportable, comparatively low-cost and operable without special training. Radar-based assessment of carotid pulse constitutes an ideal candidate for a wide-ranging and cost-effective screening device. This technology has already been studied for monitoring of vital signs such as heartbeat and respiration [7], [8]. Stiffness of the vessel wall and stenosis of the carotid reflect in changes in pulse wave configuration and velocity [9], [10], e.g., pulse wave and blood flow velocity increase [11], systolic limb becomes steeper and diastolic limb of the pulse wave tapers off [12]. These phenomena can be recorded by radar-based assessment of the carotid pulse. First radar measurements of the carotid pulse have been performed using a double sideband continuous wave radar [13]. However, neither has there been any studies on the qualitative relationship of the measurands of ultrasound carotid pulse measurement and radar-based carotid pulse measurement nor were there studies using a contactless radar system. This paper presents a theoretical derivation when comparing ultrasound and radar measurements and validates the results through synchronous measurements of both devices.

The study was approved by the ethics committee of the Friedrich-Alexander University Erlangen-Nuremberg (No. 85_15B).

II. Comparison of Ultrasound and Radar-Based Carotid Pulse Measurement

The basic anatomy of the human neck including the skeletal system, the integumentary system as well as the arterial part of the cardiovascular system are shown in Fig. 1. The common carotid artery splits up into the internal and external artery in the cranial direction. At the end of each heartbeat cycle, the left ventricle of the heart pumps oxygenated blood into the arteries. This is characterized by a rapid upstroke and a smooth but more gradual downstroke when looking at the blood flow velocity. The downstroke is interrupted only by the dicrotic notch, which is caused by a transient reversal of blood flow in the central arteries. [14]

Three types of waves occur in the vascular system: velocity, pressure and wall displacement waves [16]. While the ultrasound Doppler measures the blood flow velocity, the measurand of the radar is proportional to changes of the vessel diameter. The first step is therefore to investigate on the relation between these two quantities. To understand the events in

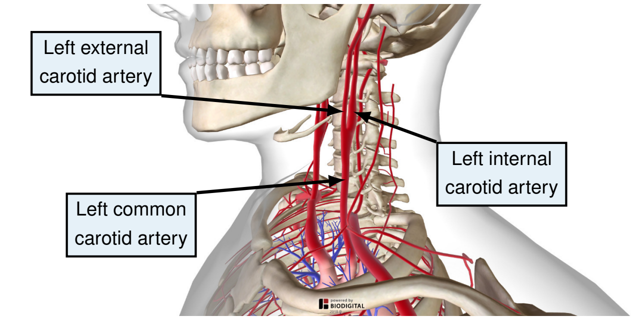

Fig. 1. The arterial system of the head and neck. Depicted are the left internal and external carotid artery as well as the left common carotid artery. [15]

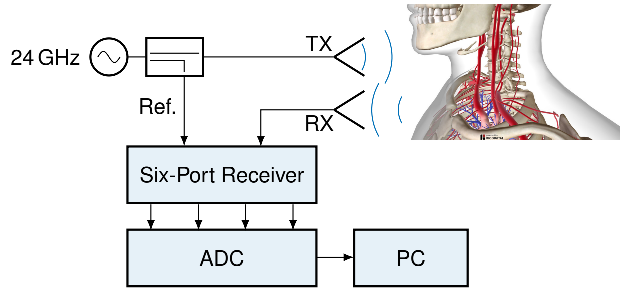

Fig. 2. Block diagram of the utilized radar system. The receiver consists of a Six-Port structure as well as integrated detectors.

the arteries, a simple but sufficient model is the following: each artery is considered as a long, isolated, circular cylindrical elastic tube. The flow is approximated to be one dimensional and the blood is considered to be homogeneous, non-viscous and incompressible. The ventricles cause the flow within the tubes with each heartbeat. Furthermore, each wave amplitude is considered small and the wave length long compared to the tube radius. This way, the radial and circumferential velocity can be neglected and the only remaining component is the longitudinal velocity $u(x, t)$ which is a function of the axial coordinate x and the time t. One basic field equation which is valid for this scenario is the equation of continuity [16]:

$$\frac{\delta A}{\delta t} + \frac{\delta}{\delta x}(uA) = 0, \tag{1}$$

with $A(x, t)$ being the cross-sectional area of the vessel which is equal to $\pi {a_i}^2$. Substitution in Eq. (1) followed by subsequent derivation leads to

$$2a_i \frac{\delta a_i}{\delta t} + u\frac{\delta {a_i}^2}{\delta x} + {a_i}^2 \frac{\delta u}{\delta x} = 0. \tag{2}$$

Since the wave amplitude is much smaller than the wavelength, $\delta a_i/\delta x \ll 1$. Additionally, small quantities of the second order can be neglected. Hence, Eq. (2) can be shortened to

$${a_i}^2 (\frac{2}{a_i}\frac{\delta a_i}{\delta t} + \frac{\delta u}{\delta x}) = 0. \tag{3}$$

Since $a_i > 0$, This can be further simplified to

$$\frac{2}{a_i}\frac{\delta a_i}{\delta t} + \frac{\delta u}{\delta x} = 0. \tag{4}$$

Finally, Eq. (4) shows that a change in the velocity u over the axial coordinate x is linearly related to a change of the vessel diameter a_i over time t. Therefore, radar displacement measurements and ultrasound velocity measurements of the carotid pulse can be directly related to each other in a qualitative manner.

III. Measurement System and Setup

As shown in Fig. 2, a bistatic continuous wave radar system is used for the contactless carotid pulse measurements.

A 24 GHz signal is generated as reference. A minor part (Ref.) is coupled into the Six-Port receiver whereas the majority is fed to the transmitter (TX) antenna. The signal is then reflected at the skin surface and received by the receiver (RX) antenna. The Six-Port is a completely passive structure which superimposes the two input signals under four relative and static phase shifts of 0°, 90°, 180° and 270°. These four output signals are converted to baseband voltages $B_{3\,...\,6}$ using integrated detectors. A movement of the target corresponds to a relative phase shift $\Delta\sigma$ between the two input signals of the Six-Port:

$$\sigma = \arg\{(B_5 - B_6) + j(B_3 - B_4)\}. \tag{5}$$

This phase shift can be converted back into a relative displacement measurement Δx by using the known wavelength $\lambda = \mathrm{c}/f$:

$$\Delta x = \frac{\Delta\sigma}{2\pi} \cdot \frac{\lambda}{2}. \tag{6}$$

Synchronous measurements of the radar system and the ultrasound device from three test persons (one female, two male), were recorded. The ultrasound probe was placed on the right carotid whereas the antenna of the radar system was focused slightly under and to the right of the larynx. The distance between the antennas and the skin was around 30 cm. A red laser beam that is placed between the antennas is used to correctly determine the antenna positioning. By putting both measurement points as close to each other as possible, the same physiological phenomenon is expected to be measured.

IV. Results

Fig. 3 shows a synchronous carotid pulse measurement using ultrasound and radar of person 1. The ultrasound measurements correspond to a blood flow velocity measurement which is represented in cm/s. The radar system measures the relative displacement change of the skin in mm. A high correlation between both signals can be observed in all three test persons. When carefully examining the radar signal in Fig. 3, it can be seen that there is a small incline right before the rapid upstroke that marks the start of each heartbeat. This is caused by the jugular vein which is located near the carotid. The atrial contraction causes a peak at this point in time. A superimposition of both pulse signals is therefore recorded at the neck. The ultrasound however will not capture the jugular vein pulse since it can separate these layers from each other.

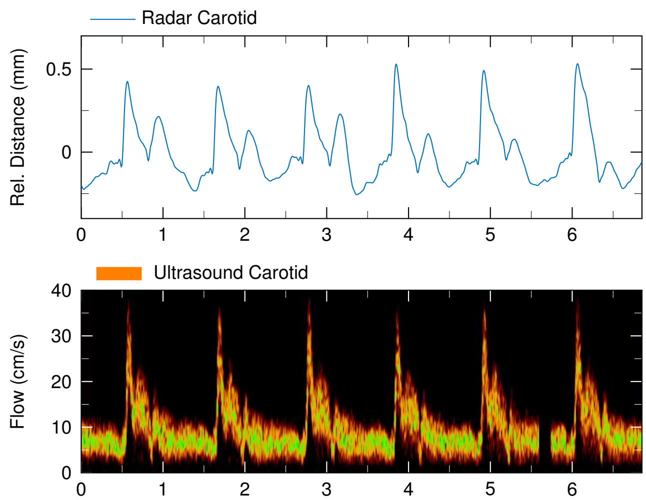

Fig. 3. Synchronous measurement of the carotid pulse using the radar and the ultrasound device.

A single heartbeat complex is extracted and visualized in Fig. 4 to distinguish the different phases of the signals. Both signals show the rapid upstroke at the beginning of the heartbeat. At this point the ejected blood arrives at the carotid artery. After reaching a peak, a more gradual downstroke begins. It is interrupted by the dicrotic notch, which is visible in both the ultrasound velocity signal as well as the radar displacement signal.

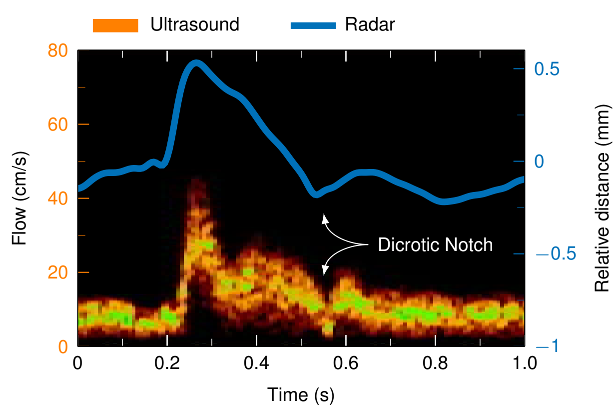

Fig. 4. A single heartbeat from a synchronous measurement using radar and ultrasound. Both signals show a high similarity and feature the same characteristics.

V. Conclusion

Ultrasound devices are the gold standard device to perform regular screenings of the carotid artery to detect vascular diseases like stenosis or any remodelling of the vessel wall. However, these devices are costly and have to be operated by a trained staff. Radar systems might prove as a low-cost, easy to use and contactless alternative to perform regular checkups of the carotid artery by analyzing the carotid pulse. To analyze the feasibility of radar systems for this purpose, it is shown that a linear relationship exists between the velocity signal of the ultrasound and the diameter change that is measured by radar. To further demonstrate the applicability, synchronous ultrasound and radar measurements were performed for different persons. When comparing the signals of both devices, a high correlation is achieved and typical carotid pulse characteristics are observed.

Acknowledgment

The research project GUARDIAN is supported by the Federal Ministry of Education and Research, Berlin, Germany, project grant No. 16SV7695.

References

[1] M. L. Bots, A. W. Hoes, P. J. Koudstaal, A. Hofman, and D. E. Grobbee, "Common carotid intima-media thickness and risk of stroke and myocardial infarction: the rotterdam study," *Circulation*, vol. 96, no. 5, pp. 1432–1437, 1997.

[2] M. Safar, J. Blacher, J. Mourad, and G. London, "Stiffness of carotid artery wall material and blood pressure in humans: application to antihypertensive therapy and stroke prevention," *Stroke*, vol. 31, no. 3, pp. 782–790, 2000.

[3] R. Lozano, M. Naghavi, K. Foreman, S. Lim, K. Shibuya, V. Aboyans, J. Abraham, T. Adair, R. Aggarwal, S. Y. Ahn *et al.*, "Global and regional mortality from 235 causes of death for 20 age groups in 1990 and 2010: a systematic analysis for the global burden of disease study 2010," *The lancet*, vol. 380, no. 9859, pp. 2095–2128, 2012.

[4] A. Di Carlo, "Human and economic burden of stroke," 2009.

[5] E. G. Grant, C. B. Benson, G. L. Moneta, A. V. Alexandrov, J. D. Baker, E. I. Bluth, B. A. Carroll, M. Eliasziw, J. Gocke, B. S. Hertzberg *et al.*, "Carotid artery stenosis: gray-scale and doppler us diagnosissociety of radiologists in ultrasound consensus conference," *Radiology*, vol. 229, no. 2, pp. 340–346, 2003.

[6] D. H. O'Leary, J. F. Polak, R. A. Kronmal, T. A. Manolio, G. L. Burke, and S. K. Wolfson Jr, "Carotid-artery intima and media thickness as a risk factor for myocardial infarction and stroke in older adults," *New England Journal of Medicine*, vol. 340, no. 1, pp. 14–22, 1999.

[7] C. Li, V. M. Lubecke, O. Boric-Lubecke, and J. Lin, "A review on recent advances in Doppler radar sensors for noncontact healthcare monitoring," *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 5, pp. 2046–2060, May 2013.

[8] G. Vinci, S. Lindner, F. Barbon, S. Mann, M. Hofmann, A. Duda, R. Weigel, and A. Koelpin, "Six-Port radar sensor for remote respiration rate and heartbeat vital-sign monitoring," *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 5, pp. 2093–2100, May 2013.

[9] E. I. Bluth, A. Stavros, K. Marich, S. Wetzner, D. Aufrichtig, and J. Baker, "Carotid duplex sonography: a multicenter recommendation for standardized imaging and doppler criteria." *Radiographics*, vol. 8, no. 3, pp. 487–506, 1988.

[10] A. Covic and D. Siriopol, "Pulse wave velocity ratio: the new gold standard for measuring arterial stiffness," 2015.

[11] W. Blackshear, D. Phillips, P. Chikos, J. Harley, B. Thiele, and D. Strandness, "Carotid artery velocity patterns in normal and stenotic vessels." *Stroke*, vol. 11, no. 1, pp. 67–71, 1980.

[12] A. J. Bonner, H. N. Sacks, and M. E. Tavel, "Assessing the severity of aortic stenosis by phonocardiography and external carotid pulse recordings," *Circulation*, vol. 48, no. 2, pp. 247–252, 1973.

[13] S. Pisa, E. Pittella, E. Piuzzi, O. Testa, and R. Cicchetti, "A double sideband continuous wave radar for monitoring carotid artery wall movements," in *2017 IEEE MTT-S International Microwave Symposium (IMS)*, June 2017, pp. 1007–1010.

[14] S. R. Braun, H. Walker, W. Hall, and J. Hurst, "Clinical methods, the history, physical, and laboratory examinations," 1990.

[15] Biodigital Inc., "Biodigital human anatomy and disease platform," https://human.biodigital.com/index.html [Online, accessed Mar. 7, 2018].

[16] Y.-C. Fung, *Biomechanics: motion, flow, stress, and growth*. Springer Science & Business Media, 2013.