Technical note

■Title

First noncontact millimeter-wave radar measurement of heart rate in great apes: validation in chimpanzees (*Pan troglodytes*)

Running title: Noncontact heart rate measurement in great apes

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■Abstract

Heart rate is a crucial vital sign and a valuable indicator for assessing the physical and psychological condition of a target animal. While medium- and long-term stress levels have been evaluated by measuring bioactive substances in samples such as urine, feces, and body hair, it is assumed that short-term changes can be measured by measuring the changes in physical and psychological state by comprehending the heart rate. Heart rate has been measured using a contact-type device; however, the device burdens the target animals and that there are risks associated with anesthesia during installation. This study explores the application of heartbeat measurement techniques using millimeter-wave radar, primarily developed for humans, as a remote method for measuring the heart rate of great apes. This approach has yielded significant insights into the evolutionary history of humans. Through a measurement test conducted on two chimpanzees, we observed a remarkable correspondence between the peak frequency spectrum of heart rate estimated using millimeter-wave radar and the mean value obtained from electrocardiograph data, thereby validating the accuracy of the method. To the best of our knowledge, this is the first demonstration of the precise measurement of great apes' heart rate using millimeter-wave radar technology. Consequently, this study unveils the potential for establishing a health management system for endangered great apes, estimating their metabolic rate, and elucidating social stressors.

■Keywords

noncontact measurement, vital sign, heart rate, millimeter-wave ultrawide-band array radar, animal welfare

■Research Highlights

- Applied millimeter-wave radar measured chimpanzees heart rate accurately, marking the first use of this technology in great apes.

- Millimeter-wave radar heart rate measurement holds promise for managing the health of endangered great apes.

■Introduction

Nonhuman primates have been studied extensively to gain insights into the evolutionary basis of human physical and psychological traits (Hirata, 2007; Myowa-Yamakoshi, 2012). In recent years, heart rate, a vital sign, has garnered substantial attention in understanding the physical and psychological states of nonhuman primates (Whitham, 2016; Wascher, 2021). Previous research has measured bioactive substances to assess medium- and long-term stress levels (Anestis, 2005). Measuring various hormones for evaluating an individual's physical and psychological state over a medium- to long-term timeframe (i.e., the duration in which samples such as feces, urine, and body hair are produced) is valuable (Preis, 2018). However, the challenge lies in the limited availability of these samples. Self-directed behaviors, such as self-scratching, have been considered relatively short-term stress indicators (Kutsukake, 2003; but see Duboscq et al. 2016). Nonetheless, they fail to identify stressors that may not be reflected in behavior. Heart rate, however, can serve as an indicator of short-term psychological stressors, as it increases under high psychological load (cf. Wascher, 2021). In one notable study, Aureli (1999) observed a decrease in heart rate during grooming in rhesus macaques (*Macaca mulatta*), indicating that grooming can alleviate psychological stress. Additionally, heart rate positively correlates with metabolic rate, allowing for the inference of physical load from heart rate variability (Halsey et al. 2019).

As mentioned earlier, understanding heart rate enables unconventional analogies to the physical and psychological state of the target animal, including behavior, and physiologically active substances. However, heart rate measurement traditionally required the use of equipment that larger animals could remove (Koda et al. 2015). Additionally, when studying social behavior, the presence of such equipment may influence social interactions and responses from other individuals. Furthermore, the physical burden imposed by wearing the devices cannot be disregarded. Animals that lack a trusting relationship with humans may require anesthesia for device attachment, which is burdensome and carries the risk of complications and mortality (Portier & Ida, 2020).

To address these challenges, several remote methods have emerged in recent years for capturing the heart rate of target individuals. One such method is video analysis (Wang et al. 2023). This technique allows heart rate estimation from past videos and eliminates the need for specialized equipment. However, it necessitates a complex analysis process, including identification of the area to be analyzed in the video and correction for environmental light exposure. Particularly in outdoor environments strongly influenced by rapidly changing natural light due to cloud cover and atmospheric conditions, e.g., under wild conditions, the success of video-based heart rate estimation is expected to be limited.

The objective of the present study was to apply remote heart rate measurement using millimeter-wave radar technology, originally developed for humans, in great apes. Millimeter-wave radar technology captures subtle body surface movements associated with heartbeat and breathing using high-frequency radar, enabling the estimation of vital information such as heart rate and respiration (Sakamoto et al. 2016). The radar frequency used in this study, namely the 79 GHz band, is commonly used in several countries for various applications, including automotive collision avoidance, with limited radiation as stipulated by the regulation norms of each country to avoid adverse effects to the human body. Therefore, this technology could be employed internationally to measure the heart rate of target individuals while considering their welfare (cf. Takeda, Sato, & Sugawara, 2000).

Millimeter-wave radar technology has been successfully applied to animals other than humans, including horses (*Equus caballus*) (Matsumoto et al. 2022), cows (*Bos taurus*) (Tuan et al. 2022), and rhesus monkeys (*M. mulatta*) (Sakamoto et al. 2023). Although there have been prior systems for monitoring chimpanzee respiration using radar analysis at a relatively low frequency, i.e., 10.525 GHz (Kindt & Spelman, 1979), to the best of our knowledge, this study represents the first application of millimeter-wave radar technology in chimpanzees and large apes.

■Method & Results

Measurements were taken on October 5, 2022, at Kumamoto Sanctuary Wildlife Research Center, Kyoto University. The study involved one adult male chimpanzee named Musashi and one adult female chimpanzee named Nacky, both housed at Kumamoto Sanctuary, Wildlife Research Center, Kyoto University (refer to Table 1 for details). The experiments were conducted during the annual health checks of the chimpanzees. Musashi was anesthetized via intramuscular injection of ketamine hydrochloride (9 mg/kg), whereas Nacky was first orally administered droperidol (0.17 mg/kg) mixed with fruit juice for sedation, followed by intramuscular injection of ketamine hydrochloride (9 mg/kg). The experimental protocol was approved by the Animal Experimentation Committee of the Wildlife Research Center, Kyoto University (WRC-2022-KS002A).

A frequency-modulated continuous wave radar system with a center frequency of 79 GHz, a center wavelength of 3.8 mm, and an occupied bandwidth of 3.9 GHz was used. The radar array consisted of a multiple-input multiple-output (MIMO) array with three transmitting and four receiving elements. The individual radar array elements had beamwidths of plus and minus 4 degrees in the E-plane and plus and minus 35 degrees in the H-plane. The transmitting elements were spaced 7.6 mm apart, whereas the receiving elements were spaced 1.9 mm apart. In the experimental setting, the MIMO array was approximated using a virtual linear array with a 12-element configuration and half-wavelength element spacing. Each measurement lasted 28 s, with a slow-time sampling interval of 6.9 ms.

For the experiments, both the array radar system and a two-electrode electrocardiogram (ECG) sensor were used simultaneously to evaluate the accuracy of heartbeat measurements for the two anesthetized chimpanzees (A: Musashi, and B: Nacky) individually while they lay in a supine position on a bed (Figure 1). The ECG sensor (biosignalsplux) from PLUX wireless biosignals (Lisboa, Portugal) was solely used to assess the accuracy of radar-based measurements. The radar system was positioned approximately 0.7 m away from the chimpanzee, directly above the front chest wall. Radar signals were directed toward the upper torso, and the reflected echoes were recorded. Simultaneously, ECG electrodes were manually attached to an arm and leg by an operator.

To analyze the radar information, a radar image was generated based on complex-valued signals as a function of time, using the range, and angular resolutions of the radar system. Time-averaged complex components were subtracted from each signal corresponding to a specific range and angle. The image was then analyzed to identify the pixel with the largest average power, and the phase of that pixel was extracted as a real-valued displacement over time. A bandpass filter was applied to suppress low-frequency components related to body motion and high-frequency components related to receiver noise. Fourier transform was subsequently performed on the filtered displacement waveform to obtain an estimate of the spectral density function in the frequency domain. Similar Fourier transform analysis was applied to the ECG signals to obtain their corresponding spectral density function in the frequency domain. Figures 2 and 3 show these estimates of normalized spectral density functions for comparison.

Figure 2 (Experiment 1) illustrates the power spectral density functions estimated from ECG (red line) and radar (black line) for chimpanzee A (Musashi). The ECG reference data indicated a heartbeat frequency of 1.41 Hz. The spectral density function exhibited the fundamental frequency of 1.41 Hz, as well as higher-order harmonics at 2.82, 4.23, and 5.64 Hz. The radar-based spectral density function showed good agreement with the higher-order harmonics in the ECG spectrum, although the peak corresponding to the fundamental frequency was less distinct. This discrepancy can be attributed to the interference of lower-frequency components at the fundamental frequency by the strong respiratory component present in the radar signals.

Figure 3 (Experiment 2) illustrates the power spectral density functions estimated from ECG (red line) and radar (black line) for chimpanzee B (Nacky). The ECG reference data indicated a heartbeat frequency of 2.02 Hz. The fundamental frequencies found in the spectra obtained from the radar and ECG data are in good agreement, with each other, whereas their higher harmonics are not clearly matched.

■Discussion

The heart rates estimated for chimpanzees through millimeter-wave radar measurements in this study (Experiment 1: 1.41 Hz; Experiment 2: 2.02 Hz) did not significantly deviate from previous reports (1.55 Hz; Boysen & Berntson, 1989) or actual contact-type measurements. This indicates that millimeter-wave radar measurements can accurately estimate heart rate. Despite chimpanzees having muscular bodies and thick body hair, which raised uncertainties about measuring their heart rate in a similar manner to measurements in humans, the results of this study demonstrated the feasibility of noncontact heart rate measurement through analysis of subtle body surface movements in chimpanzees, expanding its potential application in animal psychology and wild primatology.

Experiment 2 did not exhibit higher accuracy compared with Experiment 1. Based on the chimpanzee videos, subtle shaking of the arms and legs of the chimpanzees was observed. This factor is presumed to have reduced the accuracy of heart rate estimation. Developing a technique that enables heart rate estimation for individuals in a moving state is a future challenge (Iwata et al. 2021).

Body surface movements are common among various animal species, suggesting a high potential for applying this method in large apes other than chimpanzees. Measuring the heart rate of apes in captivity can aid in the preservation of endangered ape species through regular health checkups. Additionally, by measuring the heart rate of wild apes, their health status can be assessed, providing valuable information for species conservation. Although the present study did not include measurement of respiration concurrently, the results suggest that it is possible to measure not only heart rate but also respiration rate in both samples, as the body surface movement associated with respiration is more prominent and easily captured.

Experiments conducted on humans have demonstrated that the radar technology used in this study can localize the positions of multiple individuals with a single device (Koda et al. 2021). Therefore, the method of collecting vital information from multiple individuals using a single measuring device could potentially be applied to nonhuman primates in the future. Considering zoonosis control measures (Santarpia et al. 2020), this approach holds promise for the health management of captive animals, such as those in zoos. For instance, in the future, it may be possible to use radar to measure the heartbeat of a sleeping animal while simultaneously localizing its location and setting threshold values to alert users in case of abnormalities. The ability to facilitate daily health management of multiple individuals is a significant advantage of millimeter-wave radar technology over other remote heart rate measurement methods.

Future perspectives entail the development of analytical methods that can effectively filter out the movement of the target individual as noise, as well as validation in other great ape species. Concurrently, heart rate data of chimpanzees in both captive and wild settings will be collected to advance research in various fields. For example, chimpanzees actively participate in cognitive psychological experiments, providing valuable insights into the cognitive evolution of humans. Millimeter-wave radar heart rate measurements can provide additional fundamental information for such cognitive experiments (cf. Sato et al. 2018). Furthermore, applying this method to large apes in the wild holds potential for elucidating stressors within social groups and more accurately estimating metabolic rates, which was previously challenging.

■Acknowledgments

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■Conflict of interest

The authors declare that they have no conflicts of interest.

■Author Contributions

Takuya Matsumoto: Conceptualization (lead); data curation (lead); investigation (equal); methodology (equal); writing - original draft (lead); writing-review & editing (equal).

Itsuki Iwata: Formal analysis (lead); investigation (equal); methodology (equal); validation (lead); writing - original draft (supporting); writing-review & editing (equal).

Takuya Sakamoto: Formal analysis (supporting); investigation (equal); methodology (equal); validation (supporting); writing-review & editing (equal).

Satoshi Hirata: Conceptualization (supporting); data curation (supporting); investigation (equal); methodology (equal); writing-review & editing (equal).

■References

Anestis, S. F. (2005). Behavioral style, dominance rank, and urinary cortisol in young chimpanzees (Pan troglodytes). *Behaviour*, 142(9-10), 1245-1268. doi: 10.1163/156853905774539418

Aureli, F., Preston, S. D., & de Waal, F. (1999). Heart rate responses to social interactions in free-moving rhesus macaques (Macaca mulatta): a pilot study. *Journal of Comparative Psychology*, 113(1), 59-65. doi:10.1037/0735-7036.113.1.59.

Boysen, S. T., & Berntson, G. G. (1989). Conspecific recognition in the chimpanzee (Pan troglodytes): cardiac responses to significant others. *Journal of Comparative Psychology*, 103(3), 215-220. doi:10.1037/0735-7036.103.3.215

Duboscq, J., Romano, V., Sueur, C., & MacIntosh, A. J. (2016). Scratch that itch: Revisiting links between self-directed behaviour and parasitological, social and environmental factors in a free-ranging primate. *Royal Society Open Science*, 3(11), 160571. doi:10.1098/rsos.160571

Halsey, L. G., Green, J. A., Twiss, S. D., Arnold, W., Burthe, S. J., Butler, P. J., Cooke, S. J., Grémillet, D., Ruf, T., Hicks, O., Minta, K. J., Prystay, T. S., Wascher, C. A. F., & Careau, V. (2019). Flexibility, variability and constraint in energy management patterns across vertebrate taxa revealed by long-term heart rate measurements. *Functional Ecology*, 33(2), 260-272. doi:10.1111/1365-2435.13264

Higham, J. P., Maclarnon, A. M., Heistermann, M., Ross, C., & Semple, S. (2009). Rates of self-directed behaviour and faecal glucocorticoid levels are not correlated in female wild olive baboons (Papio hamadryas anubis). *Stress*, 12(6), 526-532. doi:10.3109/10253890902756565

Hirata, S., & Fuwa, K. (2007). Chimpanzees (Pan troglodytes) learn to act with other individuals in a cooperative task. *Primates; Journal of Primatology*, 48(1), 13-21. doi:10.1007/s10329-006-0022-1

Iwata, S., Koda, T., & Sakamoto, T. (2021). Multiradar data fusion for respiratory measurement of multiple people. *IEEE Sensors Journal*, 21(22), 25870-25879. doi:10.1109/jsen.2021.3117707

Kindt, C. W., & Spelman, F. A. (1979). Monitoring and apnea alarm for infant primates: practical and research applications. In G. C. Ruppenthal & D. J. Reese (Ed.), *Nursery Care of Nonhuman Primates* (pp. 215-225). Boston, MA: Springer US.

Koda, N., Machida, S., Goto, S., Nakamichi, M., Itoigawa, N., & Minami, T. (1998). Cardiac and behavioral responses to humans in an adult female japanese monkey (Macaca fuscata). *Anthrozoös*, 11(2), 74-78. doi:10.2752/089279398787000797

Koda, T., Sakamoto, T., Okumura, S., & Taki, H. (2021). Noncontact respiratory measurement for multiple people at arbitrary locations using array radar and respiratory-space clustering. arXiv preprint arXiv:2101.12422.

Kutsukake, N. (2003). Assessing relationship quality and social anxiety among wild chimpanzees using self-directed behaviour. *Behaviour*. 140(8-9), 1153-1171. doi: 10.1163/156853903322589687

Matsumoto, T., Okumura, S., & Hirata, S. (2022). Non-contact respiratory measurement in a horse in standing position using millimeter-wave array radar. *Journal of Veterinary Medical Science*, 84(10), 1340-1344. doi:10.1292/jvms.22-0238

Myowa-Yamakoshi, M., Scola, C., & Hirata, S. (2012). Humans and chimpanzees attend differently to goal-directed actions. *Nature Communication*, 3, 693. doi:10.1038/ncomms1695

Portier, K., & Ida, K. K. (2020). Editorial: Anesthetic risk and complications in veterinary medicine. *Frontiers in Veterinary Science*, 7, 397. doi:10.3389/fvets.2020.00397

Preis, A., Samuni, L., Mielke, A., Deschner, T., Crockford, C., & Wittig, R. M. (2018). Urinary oxytocin levels in relation to post-conflict affiliations in wild male chimpanzees (Pan troglodytes verus). *Hormones and Behavior*, 105, 28-40. doi:10.1016/j.yhbeh.2018.07.009

Rong, Y., Dutta, A., Chiriyath, A., & Bliss, D. W. (2021). Motion-tolerant non-contact heart-rate measurements from radar sensor fusion. *Sensors (Basel)*, 21(5). doi:10.3390/s21051774

Rzucidlo, C. L., Curry, E., & Shero, M. R. (2023). Non-invasive measurements of respiration and heart rate across wildlife species using Eulerian video magnification of infrared thermal imagery. *BMC Biology*, 21(1), 61. doi:10.1186/s12915-023-01555-9

Sakamoto, T., Imasaka, R., Taki, H., Sato, T., Yoshioka, M., Inoue, K., Sakai, H. (2016). feature-based correlation and topological similarity for interbeat interval estimation using ultrawideband radar. *IEEE Transactions on Bio-Medical Engineering*, 63(4), 747-757. doi:10.1109/TBME.2015.2470077

Sakamoto,T., Sanematsu, D., Iwata, I., Minami, T., & Myowa, M. (2023). Radar-based respiratory measurement of a rhesus monkey by suppressing nonperiodic body motion components, arXiv:2306.16712

Santarpia, J. L., Rivera, D. N., Herrera, V. L., Morwitzer, M. J., Creager, H. M., Santarpia, G. W., Crown, K. K., Brett-Major, D. M., Schnaubelt, E. R., Broadhurst, M. J., Lawler, J. V., Reid, S. P., & Lowe, J. J. (2020). Aerosol and surface contamination of SARS-CoV-2 observed in quarantine and isolation care. *Scientific Reports*, 10(1), 12732. doi:10.1038/s41598-020-69286-3

Sato, Y., Kano, F., & Hirata, S. (2018). Cutting-edge infrared thermography as a new tool to explore animal emotions. *Japanese Journal of Animal Psychology*, 68(1), 1-15. doi:10.2502/janip.68.1.7

Spelman, F., & Kindt, C. (1979). Monitoring and apnea alarm for infant primates: Apparatus. Nursery care of nonhuman primates, 203-213.

Takeda, K.-i., Sato, S., & Sugawara, K. (2000). The number of farm mates influences social and maintenance behaviours of Japanese Black cows in a communal pasture. *Applied Animal Behaviour Science*, 67(3), 181-192. doi:10.1016/S0168-1591(99)00124-0

Tuan, S.-A., Rustia, D. J. A., Hsu, J.-T., & Lin, T.-T. (2022). Frequency modulated continuous wave radar-based system for monitoring dairy cow respiration rate. *Computers and Electronics in Agriculture*, 196. doi:10.1016/j.compag.2022.106913

Wang, D., Eckert, J., Teague, S., Al-Naji, A., Haun, D., & Chahl, J. (2023). Estimating the cardiac signals of chimpanzees using a digital camera: validation and application of a novel non-invasive method for primate research. *Behavior Research Methods*. doi:10.3758/s13428-023-02136-y

Wascher, C. A. F. (2021). Heart rate as a measure of emotional arousal in evolutionary biology. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 376(1831), 20200479. doi:10.1098/rstb.2020.0479

Whitham, J. C., & Miller, L. J. (2016). Using technology to monitor and improve zoo animal welfare. *Animal Welfare*, 25(4), 395-409. doi:10.7120/09627286.25.4.395

■Tables and Figure Legends

Table 1. Demographic characteristics and experimental conditions of chimpanzees

The “Experiment” column indicates the experiment number. In the “Sex” column, “F” represents females, and “M” represents males. The “Birth year” and “Age” columns display the estimated birth year and age of the chimpanzees in October 2022, respectively. The “GAIN ID” column provides the ID of the chimpanzees in the Great Ape Information Network (GAIN; https://shigen.nig.ac.jp/gain/index.jsp). The “Place,” “State of anesthesia,” and “Activity” columns describe the location of the chimpanzees, their anesthesia condition, and movements during the experiments, respectively.

Figure 1. Experimental setup for Experiment 1.

The white arrow indicates the array radar equipment, whereas the dotted arrow indicates the placement of ECG sensors. Experiment 2 had a setup similar to that shown in this figure.

Figure 2.

Power spectral density functions estimated from ECG (red line) and radar (black line) for chimpanzee A (Musashi)

Figure 3.

Power spectral density functions estimated from ECG (red line) and radar (black line) for chimpanzee B (Nacky)

Table 1

Experiment	Name	Sex	Birth year	Age	GAIN ID	Place	State of anesthesia	Activity
1	Musashi	M	1975(estimated)	47(estimated)	0417	examination table	Rest	No activity
2	Nakki	F	1975(estimated)	47(estimated)	0268	examination table	half awake	Cramps in one arm

Figure 1

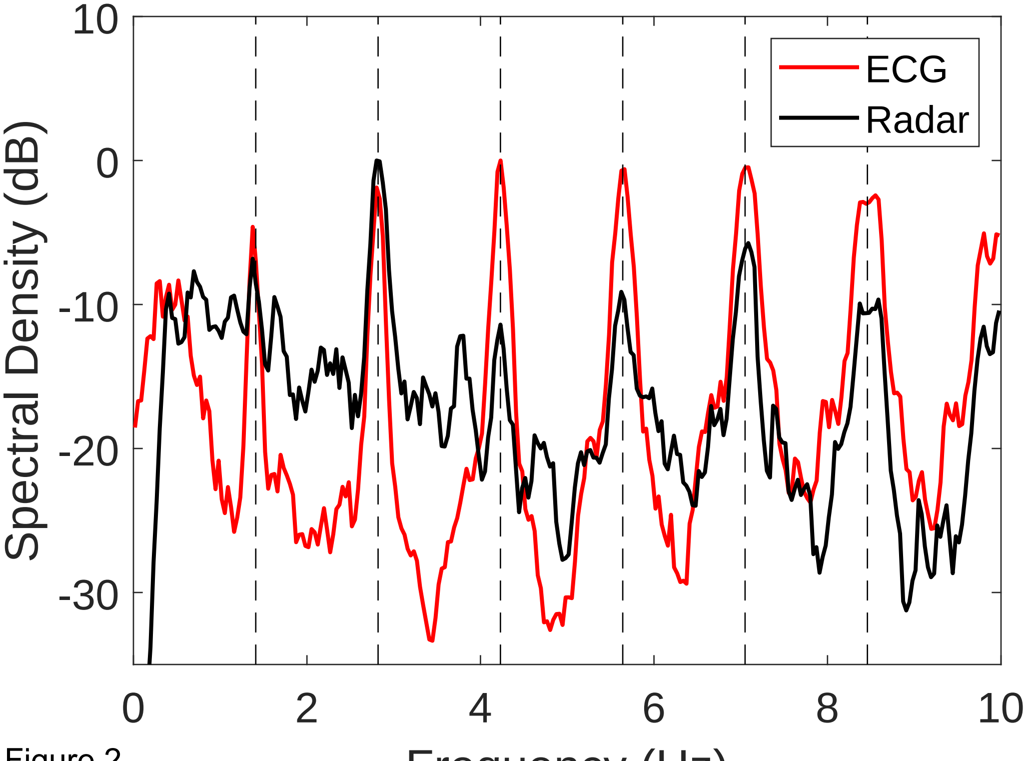
10
0
-10
-20
-30
Spectral Density (dB)
0
2
4
6
8
10
Frequency (Hz)
ECG
Radar

Figure 2

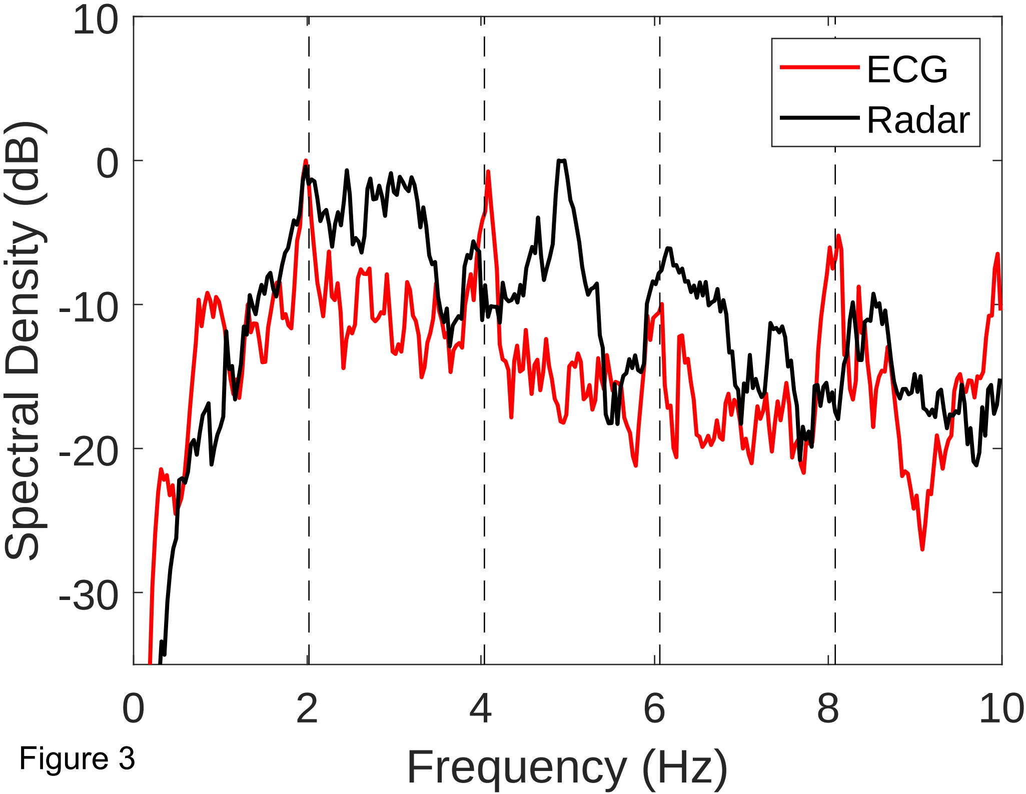
10
0
-10
-20
-30
Spectral Density (dB)
0
2
4
6
8
10
Frequency (Hz)
ECG
Radar

Figure 3