Title:

Non-contact respiratory measurement of large quadruped animals using millimeter-wave array radar

Takuya Matsumoto[1, 2, *], Shigeaki Okumura[3], and Satoshi Hirata[4]

[1]Faculty of Science, Shinshu University, 3-1-1 Asahi, Matsumoto, Nagano, 390-8621, Japan

[2]Research Institute for Humanity and Nature, 457-4 Motoyama, Kamigamo, Kita, Kyoto, 603-8047, Japan

[3]MaRI Co., Ltd. Room No. 104, 1st Floor, Building 9, 91 Chudo-ji Awata-cho, Shimogyo-ku, Kyoto-shi, Kyoto, 600-8815, Japan

[4]Wildlife Research Center, Kyoto University, 2-24 Tanaka Sekiden-cho, Sakyo-ku, Kyoto-shi, Kyoto, 606-8203 Japan

***Corresponding author**

Takuya Matsumoto

Faculty of Science, Shinshu University, 3-1-1 Asahi, Matsumoto, Nagano, 390-8621, Japan

Phone: +81 263 37 2532; E-mail: matsumoto_t@shinshu-u.ac.jp

Running head: NON-CONTACT RESPIRATORY MEASUREMENT

Conflict of Interest

The authors declare no conflict of interest.

Author contributions

TM wrote the main manuscript text, TM and SH prepared Figure 1, and SO prepared Figures 2–6. All authors reviewed the manuscript.

Abstract

This study aimed to apply radar technology to large quadruped animals. We first developed a non-contact respiration measurement system using millimeter-wave array radar for horses. Specifically, we measured the respiration of stationary domestic horses in stables. Simultaneously, we measured the respiration rate using infrared thermography and developed a method for analyzing the radar information while verifying the rate of agreement. Our results suggested that the radar technology detected breathing and accurately measured the respiration of a horse, despite variation in the breathing frequency. To our knowledge, a non-contact respiration measurement system using millimeter-wave array radar has been applied to large animals in an upright position for the first time, demonstrating its potential application to animal husbandry and animal welfare.

Keywords: millimeter-wave array radar, quadruped animals, radar technology, respiration rate

Introduction

The global epidemic of COVID-19 in 2020 and beyond has prompted the need for more stringent measures against infectious diseases. The countermeasures that have been identified to date are the avoidance of contact among individuals as much as possible and daily health monitoring [13]. However, the need to protect against infectious diseases is not limited to humans. In animal breeding and husbandry, it is important to prevent excessive contact between humans and captive animals and to perform daily health checks on the captive animals to prevent the spread of zoonotic diseases such as equine encephalitis and vesicular stomatitis [6].

Non-human animals are unable to perform medical examinations using measurement devices on their own. Non-human animals need to wear a device to monitor their health, and the wearing of the device itself can be a stressor to the animal by reducing its mobility [1]. In addition, anesthesia is required for large animals that have not yet established a trusting relationship with humans to wear the device. Anesthesia is burdensome for the animal and carries a risk of mortality owing to complications. Anesthesia in non-human animals is not completely safe, and the risk of death from anesthesia is particularly high in horses (1.4%–1.9%) compared with 0.17% in dogs [11]. Non-contact health monitoring is not only a zoonosis control measure but also reduces the impact of monitoring on target animals, such as horses, which are at high risk owing to anesthesia.

One technology that can be used to obtain vital information in a non-contact manner is radar technology. Because microwaves and millimeter waves can penetrate clothing and body hair, radar technology is one of the most valuable methods for monitoring respiration, involving movement of the body surface. In recent years, radar technology has been used in humans as well as pet dogs and cats to measure respiration rates remotely and accurately, although this approach requires a lying or sitting posture [5, 14, 15] and cannot be directly applied to quadruped animals such as horses and cows that sleep upright.

This is a pilot-study to measure respiration in large quadruped animals using millimeter-wave array radar. Simultaneously, we measured the respiration rate using infrared thermography, a conventional method of respiratory estimation established in humans [3], and developed a method for analyzing the radar information while comparing the rate of agreement. To our knowledge, for the first time, non-contact respiration measurement system using millimeter-wave array radar has been applied to large animals in an upright position, indicating the possibility of its application to animal husbandry and animal welfare.

Materials and Methods

A horse belonging to the Equestrian Club of Kyoto University [name: Canberra, date of birth: September 7, 2001, sex: male (castrated), breed: Thoroughbred] was subjected to respiration measurement from a distance of approximately 1.5 m using a radar device in March 2021 while the horse was idle in the stables of the Equestrian Club of Kyoto University. The radar system has a multiple-input and multiple-output (MIMO) antenna array composed of three transmission antennas and four receiving antennas (See supplemental information for details). The position of the radar was adjusted so that the radar captured the lateral part of the horse's body.

Simultaneously, a thermal imaging camera was used to capture images from a distance of approximately 3 m (Figure 1). Temperature measurement was conducted non-invasively using an infrared thermocamera (T650sc, FLIR Systems Japan K.K., Tokyo, Japan), with a resolution of 640 × 480 pixels and a frame rate of 3.75 Hz (Figure 2). If the position of the nose is set as the Region of Interest (ROI) in the 2D measurement of infrared thermography and the decrease in temperature of the body surface is measured continuously, the timing of respiration can be detected. To track the movement of the nose, i.e., ROI, we used DeepLabCut [7, 9]. We selected the tip and bottom of the nose and both ends of the harnesses (p1–p4) as the tracking target points. The respiration pattern is calculated using temperature data in the area enclosed by p1, p2, p′3, and p′4. (Figure 2; see supplement file for details).

This study was performed in accordance with the guidelines for proper conduct of animal experiments of Science Council of Japan. All experimental protocols were approved by the

Animal Experimentation Committee of the Wildlife Research Center, Kyoto University (WRC-2021-007A). We obtained informed consent from all subjects for the publication of identifying information/images in an online open-access publication.

Results

We conducted two experiments. The estimation results are shown in Figures 3 and 4, respectively.

In the first experiment, the horse was stable and the respiration rate was also stable over 240 s. The respiration analyzed by radar and thermography were 17 and 16 cycles, respectively. There was one discrepancy between the results of the two analyses due to the counting of a small wave captured by the radar around 50 seconds, but otherwise, there was a one-to-one correspondence between the respiration analyzed by the radar and that analyzed by thermography. In the second experiment, the respiration rate was unstable and the body movement of the horse was larger than that of the first experiment. The respiration analyzed by radar and thermography were 29 and 28 cycles, respectively. As in the first experiment, there was basically a one-to-one correspondence between the respiration analyzed by radar and that analyzed by thermography, but there was a discrepancy between the results of the two analyses around 50 and 75 seconds. A qualitative analysis of the video of the area in which the discrepancy between the breathing rates determined using the radar and that from the thermal imaging camera revealed that the horse was shaking its body.

The root mean square error between the respiratory timing measured using the thermal imaging camera and the respiratory timing obtained from the radar was 2.5 and 0.93 s in the first and second experiments, respectively. The error was calculated as the difference between the respiratory timing obtained from the radar and the closest respiratory timing obtained using thermography.

Discussion

The respiration rate of the horse in the present study was approximately 8-16 breaths per minute. We confirmed that the radar technology used in this study detects breathing, even when the frequency of breathing varies. Horses have excellent locomotion. When respiratory insufficiency occurs, their motor skills are reduced and shortness of breath occurs. Respiratory failure or impairment causes severe discomfort in humans and is believed to have similar effects in several mammals, including horses [8]. Therefore, from the viewpoint of animal welfare, it is important to measure changes in the respiratory systems of horses in a simple, non-contact manner. In this case, a radar response may detect disturbances in the resting state at night.

Body sway, rather than differences in respiratory rate, may be responsible for the error between the respiratory timing measured using the thermal imaging camera and that obtained from the radar. The radar captures displacement in the direction of the line of sight. Therefore, body sways other than breathing will be captured because body sways are bigger movement than the movement of the body surface due to breathing. The point at which the radar detects a subtle shift in body surface motion and the point at which the thermal imaging camera measures cold air entering the nose and the temperature beginning to drop are two different points of respiration, so it is not surprising that there is a discrepancy in the timing of the detected breaths (2.5 and 0.93 s as the root mean square error in the first and second experiments, respectively).

The radar technology used in this study can localize individuals and therefore does not require additional complex processing, such as thermal imaging analysis. Thermal imaging cameras that are capable of two-dimensional measurements and are accurate enough to capture the presence or absence of breathing are expensive. With the mass production of radar modules in recent years, it has become possible to obtain radar modules at a relatively low cost. Another issue is the possibility of not being able to detect breathing well when the temperature of the exhalation is similar to the ambient temperature. Radar technology is valuable in that it can be used for measurements regardless of the environment. It is highly likely that radar is also capable of measuring in the rain, and this will be verified in the future. The 79-GHz band used by this radar technology is widely used in several countries, and this technology can be applied to radars that can be used in many countries.

Several large mammals, such as horses, elephants, and giraffes, sleep in a standing position [16]. The present study is the first to report the measurement of the respiration rate of a large animal in a quadruped standing position remotely by radar technology. By modifying the module, the system can be applied to a wide range of animals with body surface amplitude changes caused by respiration.

Using radar technology with humans, it is possible to measure the respiratory rates of multiple individuals using a single radar module [4]. Future prospects include the application to animal species other than horses, the measurement of the respiratory rates of multiple horses in a stable, and the measurement of heart rates in addition to respiratory rates.

Acknowledgments

This research was financially supported by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) KAKENHI (grant number 20K20875 to Takuya Matsumoto and 18H05524 to Satoshi Hirata). We thank the Kyoto University equestrian club for cooperation in the experiments. We are grateful to Takuto Sugimoto and Tamao Maeda for experimental assistance.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

1. Blake, S., Williams, R. and Ferro de Godoy, R. 2019. A systematic review of the biomechanical effects of harness and head-collar use in dogs. Preprint at https://www.biorxiv.org/content/10.1101/759258v1.

2. Boucher, P. and Plusquellec, P. 2019. Acute stress assessment from excess cortisol secretion: fundamentals and perspectives. *Front. Endocrinol.* **10**: 749.

3. Hu, M., Zhai, G., Li, D., Fan, Y., Duan, H., Zhu, W. and Yang, X. 2018. Combination of near-infrared and thermal imaging techniques for the remote and simultaneous measurements of breathing and heart rates under sleep situation. *PLOS ONE* **13**: e0190466.

4. Koda, T., Sakamoto, T., Okumura, S. and Taki, H. 2021. Noncontact respiratory measurement for multiple people at arbitrary locations using array radar and respiratory-space clustering. *IEEE Access* **9***:* 106895–106906.

5. Kranjec, J., Beguš, S., Geršak, G. and Drnovšek, J. 2014. Non-contact heart rate and heart rate variability measurements: a review. *Biomed. Signal Process. Control* **13**: 102–112.

6. Kumar, B., Manuja, A., Gulati, B. R., Virmani, N. and Tripathi, B. N. 2018. Zoonotic viral diseases of equines and their impact on human and animal health. *Open Virol. J.* **12**: 80–98.

7. Mathis, A., Mamidanna, P., Cury, K.M., Abe, T., Murthy, V.N., Mathis, M.W. and Bethge, M. 2018. DeepLabCut: markerless pose estimation of user-defined body parts with deep learning. *Nat. Neurosci*. **21**: 1281–1289.

8. Mellor, D. J. and Beausoleil, N. J. 2017. Equine welfare during exercise: an evaluation of breathing, breathlessness and bridles. *Animals (Basel)* **7**: 41.

9. Nath, T., Mathis, A., Chen, A.C., Patel, A., Bethge, M. and Mathis, M.W. 2019. Using DeepLabCut for 3D markerless pose estimation across species and behaviors. *Nat. Protoc.* **14**: 2152–2176.

10. Padalino, B., Raidal, S.L., Knight, P., Celi, P., Jeffcott, L. and Muscatello, G. 2018. Behaviour

during transportation predicts stress response and lower airway contamination in horses. *PLOS ONE* **13**: e0194272.

11. Portier, K. and Ida, K. 2020. K. Editorial: anesthetic risk and complications in veterinary medicine. *Front. Vet. Sci.* **7**: 397.
12. Sakamoto, T., Imasaka, R., Taki, H., Sato, T., Yoshioka, M., Inoue, K., Fukuda, T. and Sakai, H. 2016. Feature-based correlation and topological similarity for interbeat interval estimation using ultrawideband radar. *IEEE Trans. Bio Med. Eng.* **63**: 747–757.
13. 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. and Lawler, J.V. 2020. Aerosol and surface transmission potential of SARS-CoV-2. *Sci Rep*. **10**: 12732.
14. Villarroel, M., Jorge, J., Meredith, D., Sutherland, S., Pugh, C. and Tarassenko, L. 2020. Non-contact vital-sign monitoring of patients undergoing haemodialysis treatment. *Sci. Rep.* **10**: 18529.
15. Wang, P, Ma, Y., Liang, F., Zhang, Y., Yu, X., Li, Z., An, Q., Lv, H. and Wang, J. 2020. Non-contact vital signs monitoring of dog and cat using a UWB radar. *Animals (Basel)* **10**: 205.
16. Zepelin, H., Siegel, J. M. and Tobler, I. 2005. Mammalian sleep. *Princ. Pract. Sleep Med.* 91–100.

Figure Legends

Figure 1. Photograph of the experimental environment. The gray arrows indicate the radar device. The dotted arrow indicates the thermal imaging camera.

Figure 2. An example of a 2D thermography image. The vertical and horizontal axes are both in pixels. The area enclosed by the dotted line is the target of the analysis.

Figure 3 The displacement measured by radar (upper panel) and the temperature measured by thermal imaging (lower panel) of a stable horse. The dotted line shows the respiratory timing. Blue areas in the upper figure show an unreliable frame area that includes high-speed movement.

Figure 4 The displacement measured by radar (upper panel) and the temperature measured by thermal imaging (lower panel) of an unstable horse. The dotted line shows the respiratory timing. Blue areas in the upper figure show an unreliable frame area that includes high-speed movement.

Figure 1

Figure 2

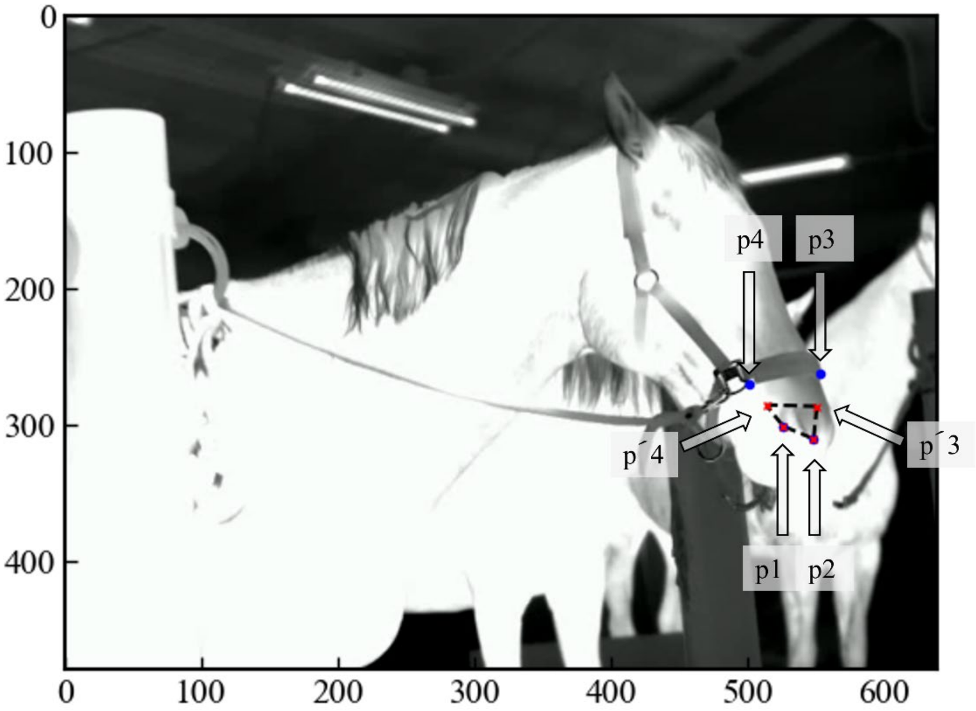
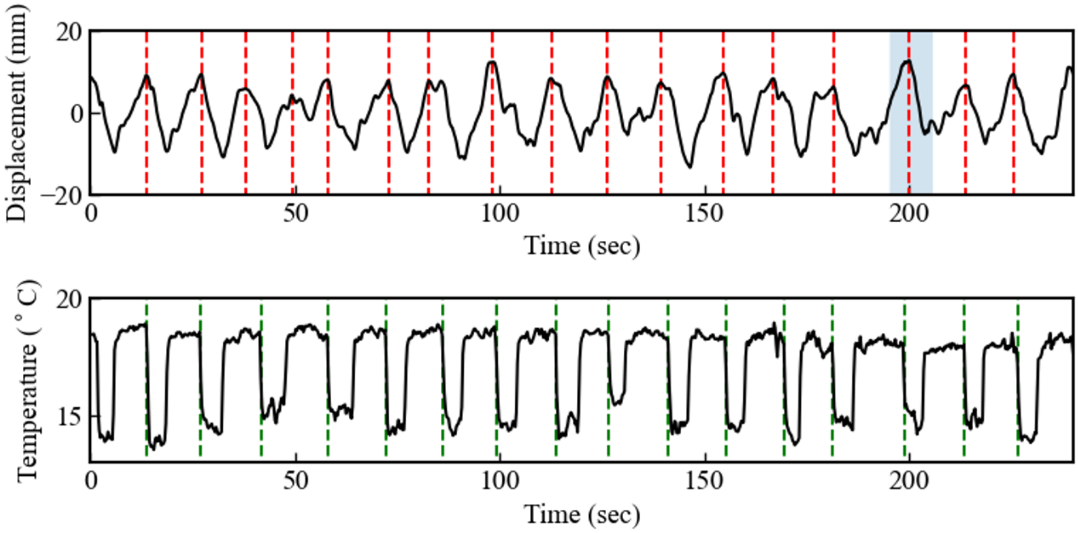
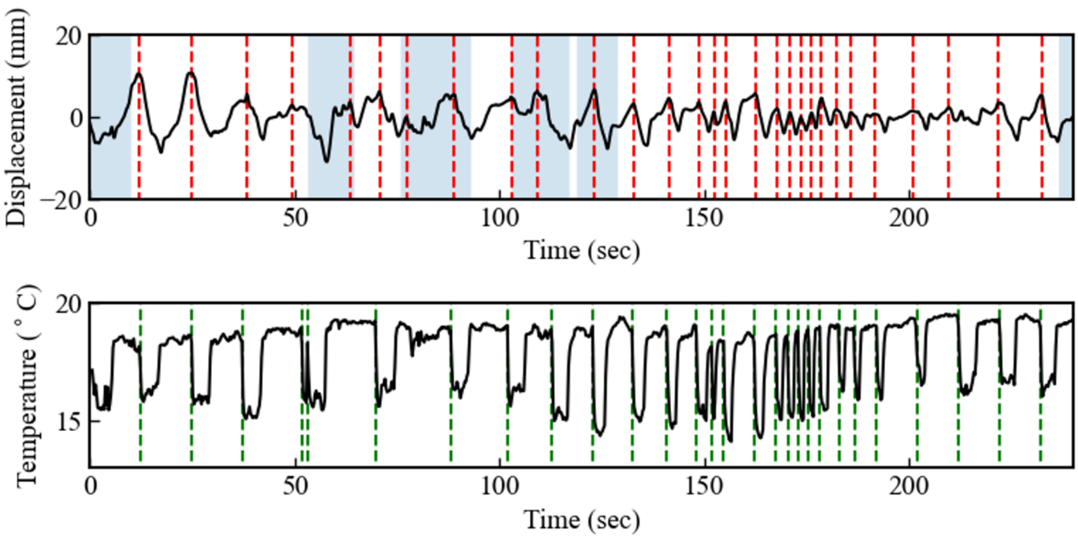


Figure 3



Displacement (mm)
20
0
−20
0
50
100
150
200
Time (sec)
Temperature (°C)
20
15
0
50
100
150
200
Time (sec)

Figure4


Displacement (mm)
20
0
−20
0
50
100
150
200
Time (sec)
Temperature (° C)
20
15
0
50
100
150
200
Time (sec)