

1 **Title:**

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

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19 **Running head: NON-CONTACT RESPIRATORY MEASUREMENT**

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21 Supplemental information

22 The central frequency of the radar was 79 GHz with a range resolution of 43 mm. The system
23 has a multiple-input and multiple-output (MIMO) antenna array composed of three transmission
24 antennas and four receiving antennas. With this system, 12 signal channels are acquired. The
25 transmission pattern of the radar is shown in Supplemental Figure 1. The three transmission
26 antennas transmit a signal with time division multiplexing. In a single data frame, 12×16 signals
27 were included, and the data were collected at an interval of 100 ms. The duration of chirp signals
28 and their intervals were 267 μs and 57 μs , respectively.

29 In this study, we used a frequency-modulated continuous wave (FMCW) radar with a 12-
30 channel MIMO linear array antenna. Using this system, we could acquire two-dimensional range-
31 angle information. The range information represents the distance from the radar to the target. The
32 angle information represents the direction of arrival of the signal, i.e., the angle of the target [4].

33 The raw signals received from the FMCW radar are in the frequency domain. We first applied
34 a Fourier transform to convert it to the range domain. A radar signal in the range domain is
35 expressed as $s_n(t, r)$, ($n = 1 \cdots 12$), where n , t , and r represent element number, time, and range,
36 respectively. We also applied a traditional beam-forming technique with a Tukey window to
37 produce the 2D complex radar image $I(t, r, \theta)$ [4].

38 As shown in Figure 1, the radar image included undesired signal from the static component,
39 e.g., metal poles. To remove the effect, we subtracted the DC component of the radar image.

$$40 \quad I'(t, r, \theta) = I(t, r, \theta) - \frac{1}{T} \int_0^T I(\tau, r, \theta) d\tau \quad (2),$$

41 where T is the duration of the DC component calculation. In this study, T was set to 250 s.
42 Because we subtracted the time averaging signal, the signal from the static components that did
43 not have the time variation component would be removed [4].

44 To identify the position of the target, we first detected the maximum power of the radar image,
45 $P(r, \theta)$, which is represented as follows:

46
$$P(r, \theta) = \frac{1}{T} \int_0^T |I(\tau, r, \theta)|^2 d\tau \quad (3)$$

47 The displacement of the body surface leads the phase rotation of the radar signal. The
48 displacement of the target is expressed as follows:

49
$$d(t) = \frac{\lambda}{4\pi} \text{unwrap}(\angle I'(t, r_0, \theta_0)) \quad (4),$$

50 where λ , r_0 , and θ_0 , represents the wavelength at the center frequency, the range portion of the
51 target, and the angle position of target, respectively [12].

52 As shown in Supplemental Figure 1, the radar transmits 16 signals over a short period of time.
53 We averaged 16 samples of $d(t)$ to improve the signal-to-noise ratio. After this process, we
54 achieved an averaged displacement $d'(t)$ with a sampling interval of 100 ms. We also applied
55 band pass filter by subtracting the signal calculated by the moving mean filter with an averaging
56 length of 20 s and applied a moving mean filter with an averaging length of 0.5 s.

57 To measure the respiration timing, we used a peak finding method implemented in SciPy 1.6.3
58 (<https://www.scipy.org/>). We assumed that the displacement related to respiration was stable over
59 60 s. We normalized the displacement with a time duration of 60 s and found peaks with a
60 prominence of > 0.5 . The overlap of the time window was 30 s.

61 When making these measurements, body movements unrelated to respiration give false results.
62 The velocity of the body surface displacement related to the respiration should not be high. Thus,
63 we removed high-speed body surface displacement. As shown in Supplemental Figure 1, we used
64 16 pulses for the estimation of high-speed body surface displacement. When the displacement
65 was larger than 0.45 mm in 15.6 ms, we considered the frame unreliable. We did not evaluate the
66 error for ± 5 s around an unreliable frame.

67

68 Temperature measurement was conducted non-invasively using an infrared thermocamera
69 (T650sc, FLIR Systems Japan K.K., Tokyo, Japan), with a resolution of 640×480 pixels and a
70 frame rate of 3.75 Hz (Figure 3). The emissivity was set at the default value of 0.95. The

71 temperature of the body surface of a horse is lower than the ambient temperature. Therefore, a
72 decrease in body surface temperature owing to the intake of air at ambient temperature is observed
73 near the nose during inhalation. If the position of the nose is set as the Region of Interest (ROI)
74 in the 2D measurement of infrared thermography and the decrease in temperature of the body
75 surface is measured continuously, the timing of respiration can be detected. The automatic
76 extraction of the position of the nose using 2D thermography with an infrared camera may allow
77 automatic measurement of the timing of breathing. Therefore, the infrared 2D images were
78 analyzed using DeepLabCut [7, 9], which is used for the skeletal tracking of animals. The
79 resulting infrared thermography movie was converted to gray scale, with the range of 10–25
80 degrees being linearly assigned to pixel values between 0 and 255. We selected the tip of the nose,
81 bottom of the nose, and both ends of the harnesses (p1–p4) and trained them using DeepLabCut.

82 Using this process, we could acquire temperature information in the ROI for DeepLabCut.
83 However, the ROI may include temperature data from unintended places, such as belt buckles.
84 We narrowed the ROI for temperature measurement related to respiration. The number of gray
85 scale pixels in the area enclosed by p1, p2, p'3, and p'4 was calculated for each frame as follows:
86 p'3 and p'4 (see Figure 2).

$$87 \quad \mathbf{p}'_3 = \frac{(\mathbf{p}_2 + \mathbf{p}_3)}{2}, \quad \mathbf{p}'_4 = \frac{(\mathbf{p}_1 + \mathbf{p}_4)}{2} \quad (1)$$

88 Since the outside temperature was lower than the horse's body surface temperature, the lower
89 5% of the ROI value was averaged and used as the measured temperature. To measure the timing
90 of breathing, we first estimated the standard temperature. We applied a moving max and minimum
91 filter with a time duration of 24 s. The result of the moving max filter $g_{\max}(t)$ and moving
92 minimum filter $g_{\min}(t)$ are shown in Supplemental Figure 2. The average of the signals after
93 the application of the moving max and minimum filter $(g_{\max}(t) + g_{\min}(t))/2$ is the standard
94 temperature. The timings that crossed the standard temperature were taken to be the intake timings.

95

96

97 **Figure Legends**

98 **Supplemental Figure 1.** The transmission pattern of the radar.

99

100 **Supplemental Figure 2.** Results of temperature measurements from a 2D thermography image.

101 The solid blue line shows $g_{\max}(t)$, the orange solid line shows $g_{\min}(t)$, the solid red line shows

102 standard temperature, and the green dotted line shows intake timings.

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