Non-Contact Vital States Identification of Trapped Living Bodies Using Ultra-Wideband Bio-Radar

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ABSTRACT Identifying the vital states of trapped survivors during post-disaster rescue missions can result in improved rescue strategies and provide injury pre-diagnosis information. The most effective rescue method is the use of bio-radar based non-contact measurements. Presently, bio-radar techniques focus on detecting and locating. Herein, a method to identify vital states with an ultra-wideband bio-radar is proposed, while simulating a trapped condition with Beagle dogs. This investigation revealed three vital stages under the trapped condition: normal, transitioning, and agonal stages. Upon entering the transitioning stage, the heart rates were apparently high, and the respiratory rates increased sharply. The temperatures dropped rapidly once passing this stage. In particular, the respiratory waveforms from the bio-radar frequently change from a normal sine-like curve to an “M”-like curve within the transitioning stage. The accurate beginning and ending of the transitioning stage are defined by a newly proposed indicator of relative occurrence frequency. Pathological observations indicated that the fragmentation of lamellar bodies within type II alveolar cells caused the insufficiency of the lung surfactant, and further resulted in the occurrence of the “M”-like curves. This pioneering work realizes the vital states identification only using a non-contact ultra-wideband bio-radar, thereby enables to infer the health conditions, life expectancy, and appropriate subsequent treatment of victims in the trapped condition. Therefore, it has the potential to promote the welfare of post-disaster trapped human victims.

INDEX TERMS Identifying vital states, lamellar bodies, lung surfactant, post-disaster rescue, respiration, ultra-wideband (UWB) bio-radar.

I. INTRODUCTION
Disasters such as earthquakes, mining accidents, and landslides usually cause a significant amount of damage, especially in heavily populated areas [1], [2]. Victims in these disasters are usually buried under the ruins, and they are unable to communicate with the outside world. Furthermore, they cannot obtain any food or water. To rescue the trapped survivors, it is necessary to detect and search the survivors firstly. Different from other non-contact measurements such as infrared and optical sensors, ultra-wideband (UWB) bio-radar is the most effective searching method mainly due to its advantages in penetrating obstacles and robustness to a variety of weather and light conditions [3]–[8]. Especially, non-contact monitoring of vital signs at in-home environment based on UWB bio-radar is increasingly becoming a hot research topic [9]. As for current post-disaster rescue studies that use UWB bio-radars, they focus mainly on the detecting and locating of the buried targets [10], [11], and a few designs attempt to distinguish the human targets from family pets under through-obstacle conditions [12], [13]. These studies can help acquire information for the accurate positions and counts of real human targets during rescue operations. However, little was known about the varieties of the survivors’ vital state under trapped conditions due to the limitations of techniques and methodologies. This information could refine the rescue missions and facilitate the successful rescue of the survivors. Identifying the vital states using UWB bio-radar based non-contact measurements, namely the current survival quality, can provide information about the survivors’ physical condition. It can serve as guidance and thereby help provide an improved rescue strategy.
For example, if the buried targets were identified to be extremely endangered with a pretty poor vital state, the rescue strategies should focus on the time and speed even though there might be some safety risks in the rescue process. Conversely, if the victims’ vital states are determined to be relatively well, then more reliable and safer methods should be implemented, although they may require a little more time. In addition, exploring the possible internal physiological causes for the transition of the vital states to the different stages, namely the damage to the targets’ internal organs and tissues, can help provide prior medical knowledge of the injury pre-diagnosis of the trapped survivors. And the pre-diagnosis information can play an important role after transporting the rescued survivors to the rear graded care center for subsequent therapy.

In this study, we found that different vital stages can be identified with UWB bio-radar based non-contact measurement by performing a post-disaster trapped condition simulation of Beagle dogs. Three vital stages were distinguished under the simulated trapped condition: normal, transitioning, and agonal stages. Upon entering the transitioning stage, the respiratory waveforms from the UWB bio-radar frequently change from a normal sine-like curve to an “M” like curve. Simultaneously, the heart rate and respiratory rate were obviously higher within this stage. The internal physiological causes for the occurrence of the “M” like curves within the transitioning stage were explored and explained by histopathology diagnosis. After the transitioning stage, the targets would enter an extremely dangerous period and die soon, which applies to the agonal stage. In particular, the “M” like curves within the transitioning stage in the dog experiments were found pretty similar to the respiratory waveforms of sobbing respiration in the neonatal respiratory distress syndrome (NRDS) of human subjects. And the pathological causes for the “M” like curves was determined the same as those of NRDS. This indicated that relevant analogue of the experimental result in the dog subjects can be found in human subjects. Further, it proved that the method of vital states identification derived from the dog-model experiments hold important reference values in human subjects.

This study establishes the process and method for groundbreaking studies in identifying different vital states only using non-contact measurements, and it provides the foundations for further researches. The experimental results are expected to promote the application of UWB bio-radar based non-contact measurements in post-disaster rescue missions and promote the safety of the trapped human victims. It could help determine the most appropriate rescue strategy for rescuers, and finally help save more lives after disasters.

II. MATERIALS AND METHODS

A. SIMULATED POST-DISASTER CONDITION

This work aims to implement a preliminary exploration of whether and how the different vital stages of post-disaster trapped victims can be identified with UWB bio-radar based non-contact measurements through animal model experiments. A literature review indicated that this topic has been rarely explored. In post-disaster rescues, the trapped survivors are usually buried under ruins and they are unable to move, nor obtain any food or water from the outside world. Therefore, the trapped condition should be a combination of several single conditions, which includes food and water deprivation, confined spaces, compression fracture due to ruins, and bleeding. To establish a feasible experimental method and explore the internal physiological causes for weakening vital states more clearly in a preliminary exploration, one single condition should be chosen to simplify the experiment. The food and water deprivation condition was chosen because it is considered to be applicable to all simulated trapped models with compound conditions.

B. SUBJECTS

Beagle dogs were chosen as the experimental subjects for the simulated trapped condition. Beagle dogs are often used as animal models in pharmacological experiments and they have been verified to be used in place of humans in bioequivalence tests because they have similar reactions to humans under many experimental conditions [14], [15]. Their physical indicators, such as respiration and heart rate, are stable and the values are close to humans’ [16]. Physiological indicators of other smaller animals, such as rabbits or mice, are unstable (the values change greatly each time) and they are significantly higher than the values of humans. For example, our pre-experiments showed that the heart rate of a New Zealand white rabbit can be more than 240 times per minute, which is almost four times greater than that of a human. Therefore, beagle dogs are more appropriate, and they should be the smallest laboratory animals that can be used in this experiment while following animal welfare principles [17], [18]. In total, four dogs were included in this experiment. Two dogs underwent the entire experimental process under the simulated trapped condition to explore a feasible staging method by combining various physical indicators of non-contact and supplementary contact measurements. The other two dogs were used for exploring the possible internal physiological causes for the transition of the vital states to the different stages.

C. NON-CONTACT MEASUREMENT OF RESPIRATION FROM UWB BIO-RADAR

Bio-radar is an arising radar technique and it is different from conventional early warning radar technologies that are mainly used for locating airplanes, ships, or missiles with a metal shell. It is mainly applied to detect the vital signs, locate targets, and distinguish different body movements, possessing great market potential in medical and rescue applications due to its advantages in penetrability of nonmetallic obstacles, stability to weather varieties, and protectiveness of privacy. Bio-radar usually consists of two parts: the radar hardware and the algorithm processing system.

The effectiveness of monitoring vital signs of animals using bio-raders has been demonstrated in previous...
researches [19]. In this study, an X4M02 (XeThru/Novelda, Oslo, Norway) UWB bio-radar system on a chip was adopted as the radar hardware to monitor the respiration as a non-contact measurement [16], [20]. The working principle of the UWB bio-radar for measuring the respiration is illustrated in Fig. 1. First, the transmitter works as a direct-RF (radio frequency) synthesizer that generates a sequence of Gaussian-like pulses. The bandwidth and center frequency of the pulses are programmable, and they are set by a 27-MHz crystal oscillator (OSC) and a 243-MHz phase-locked loop (PLL). Then, the pulses are transmitted through the transmitting antenna (TA) to detect the targets. The radiated pulses are reflected by the targeted dog’s chest, on the surface of which some micro-motion displacements occurred due to the lungs’ respiratory movement. Next, the reflected echoes were received through a receiving antenna (RA), and they are filtered, amplified, and sampled by a high-pass filter (HPF), a low noise amplifier (LNA), and a sampler, respectively. The sampling rate of the sampler was also set using the PLL and the OSC. Finally, the processed echoes were transferred to the algorithm processing system through the SPI and USB cable, and there were 17 waveforms per second within the frame. Namely, the scanning speed of the UWB bio-radar throughout the observation time was 17 Hz. The receiver sampled the reflected echoes from the targets at 23.328 GS/s and it can cover a 5 m consecutive range.

In terms of the contact measurements, an RM6240E physiological parameter acquisition system was used to monitor the respiratory signals with a piezoelectric respiratory belt transducer, an IX-B3G isolated biopotential recorder for ECG monitoring (iWorx Systems, Inc., Dover, NH), an Omron thermometer MC-347 with a 0.1 °C accuracy for anal temperature monitoring, and a SETPRO counting scale with a 0.0001 kg accuracy for weight measuring.

In order to identify the different vital stages scientifically and objectively, more physiological indicators that can reflect the physical states are needed. In the experiment, electrocardiogram (ECG), anal temperature, and weight were monitored through contact measurements as supplementary indicators. In addition, the contact measurement of the respiration that was monitored by a piezoelectric respiratory belt transducer was also implemented as a comparison indicator, which was synchronized with the UWB bio-radar respiration measurement. It was used to compare with the UWB bio-radar signals; thus, verifying the accuracy and reliability of the respiration from the UWB bio-radar. To keep the dogs stationary and obtain stable and reliable measuring results, all indicators were detected when the dogs were subjected to isoflurane anesthesia.

FIGURE 1. Working principle of the UWB bio-radar for respiration measuring. $x(t)$ represents the original micro-motion displacements on the chest caused by the expansion and contraction of the lungs’ respiratory movements. Abbreviations: SPI, serial peripheral interface; LNA, low noise amplifier; HPF, high-pass filter; OSC, oscillator; PLL, phase-locked loop; TA, transmitter antenna; RA, receiving antenna.
isoflurane displayed a slight analgesic effect, and it fulfilled an important ethical criterion for the animal experimentation according to the guidelines by the ethics committees. Throughout the entire experiment, the dogs usually regained consciousness and they could move normally within five minutes after the anesthesia was relieved. All measurements of the four Beagle dogs were obtained under the same anesthetic conditions. Therefore, the shape changes in the respiratory waveforms and the indicators’ trends during the experimental process can reflect the transitions in the vital states. However, the specific values of the indicators (heart rate or respiratory rate) may be slightly lower because of the anesthesia or the dogs’ laying down position.

**G. DATA ACQUISITION**

All vital signs, including the respiratory waveforms obtained from the non-contact UWB bio-radar and the synchronized piezoelectric respiratory belt transducer, the ECG signals, anal temperatures, and weights were recorded every 12 hours, at 9 A.M. and 9 P.M., respectively. There exist three main reasons for using this type of data collection method:

1) The supplementary indicators such as the ECG, anal temperature, and weight, were detected to help identify the different vital stages more scientifically and objectively. These indicators were obtained through contact measurements. It is necessary to detect these indicators when the dogs were subjected to isoflurane anesthesia. In order to reduce the disturbance to the transition of the dogs’ vital states introduced by the anesthesia, the number of data acquisitions must be minimized.

2) The transition of the vital states in the dogs upon depriving them of food and water is a slow process [24]. Therefore, collecting the data twice a day can meet the demand of minimal number of data acquisitions.

3) Collecting data at 9 A.M. and 9 P.M. ensures that the data are distributed across both daytime and nighttime. This helps in eliminating the effect of the circadian alternation on the vital signs such as heart rate and respiratory pattern.

**III. RESULTS AND DISCUSSION**

**A. STAGING OF VITAL STATES**

Two healthy Beagle dogs (1 male and 1 female), which were each approximately one year old, underwent the experimental process under the condition of food and water deprivation. They were within a cage to simulate the trapped space, except when measuring the contact and the non-contact vital signs. Their excretions were cleaned up in time. All vital signs, including the respirations that were monitored by the non-contact UWB bio-radar and the synchronized piezoelectric respiratory belt transducer, the ECG signals, anal temperatures, and weights were recorded every 12 hours, at 9 A.M. and 9 P.M., respectively. The experimental setup is shown in Fig. 2(a). The dogs were subjected to isoflurane anesthesia by inhaling a mixture of isoflurane and air at a controlled ventilation volume while the measurements were performed.

The comparison results of the synchronous respiratory measurement by the UWB bio-radar and piezoelectric respiratory belt transducer are shown in Fig. 2(b). The two waveforms matched closely and rendered similar beat-to-beat intervals. This verified the accuracy and reliability of the respiration measurements by the UWB bio-radar in the experiment, because the conventional piezoelectric belt transducer is usually regarded as the “gold standard.”

**B. TRANSITIONING STAGE**

The overall survival time of the two dogs was 31 days for the female, and 29 days for the male. The trends of heart rate, temperature, respiratory rate from the UWB bio-radar, and the weight of the two dogs are illustrated in Fig. 3. At the beginning of the simulated trapped condition, the two healthy dogs were in the normal stages. Their weights, as shown in Fig. 3(g) and Fig. 3(h), dropped linearly with time and declined by approximately 0.075 kg on average for both dogs.

But it is worth noting that all of the other physiological indicators existed a special period where the corresponding values were obviously different or they were about to drop rapidly. As shown in Fig. 3(a) and Fig. 3(b), the heart rates within the intervals indicated by the dashed boxes are significantly higher than the other sections for both of the dogs. In particular, the heart rate of the female reached 2.7 Hz within the interval, which is almost twice as high in comparison to the normal values. The temperature values were mostly stable and only fluctuated slightly (including during the period within the dashed boxes), as shown in Fig. 3(c) and Fig. 3(d). However, they dropped rapidly at the end of the intervals for both of the dogs. The rapid decline in the temperature indicated that the dogs were in an extremely dangerous health state since they were close to death. When considering the respiratory rates that were measured by the UWB bio-radar as illustrated in Fig. 3(e1) and Fig. 3(f1), they displayed sharp rises within the intervals for both dogs.

Based on the aforementioned significant changes, the periods within the dashed boxes were preliminarily judged as the transitioning stage before entering the extremely dangerous states. The transitioning stages indicated that the vital states of the trapped targets would deteriorate sharply and they...
FIGURE 3. Trends of heartbeat, temperature, respiratory rate by the UWB bio-radar, and weight of the two dogs. (a), (c), (e) and (g) belong to the female. (b), (d), (f) and (h) belong to the male. The curves of E1 and F1 represented the trends of respiratory rates. The curves of E2 and F2 were the calculated values of the corresponding relative occurrence frequency of the ‘M’ like curves. If there were blue symbols (▼) above the curves of E2 and F2, it represented that the ‘M’ like curves of respiratory waveforms were observed in the current measurements from the UWB bio-radar. The weights of the two dogs declined linearly with the curves approximating to straight lines, as shown in (g) and (h). Other physiological indicators all had a period where the corresponding values were significantly higher than others (heart rate and respiratory rate), or were about to drop rapidly (temperature), as the periods shown within the dashed boxes.

C. AGONAL STAGE

After the transitioning stage, the dogs entered the agonal stage since they were on the verge of death. The heart rates and temperatures dropped sharply. In particular, the temperatures declined from a normal level of 38 °C to less than 35 °C, and they died after a few days. Simultaneously, the “M” like curves basically disappeared, and the respiratory waveforms from the UWB bio-radar within the agonal stage changed back to the sine like curves. The main difference of these waveforms from those in the normal stage was that the amplitude and frequency of the respiration within the agonal stage declined considerably.

D. BEGINNING AND ENDING OF THE TRANSITIONING STAGE

The transitioning stages were identified by the different trends of the continuously monitored physical indicators and the frequently occurring “M” like curves of the respiratory waveforms. In particular, the “M” like curves did not exist or they essentially disappeared during the normal or agonal stages. Therefore, we present a reasonable method to define the accurate beginning and ending of the transitioning stages by observing the relative occurrence frequency of the “M” like curves from the UWB bio-radar respiratory waveforms. In Fig. 3(e2) and Fig. 3(f2), a blue symbol (▼) above the curves for E2 or F2 at the corresponding time index indicates that the “M” like curves were observed in the current UWB-bio-radar measurements. Then, we defined an indicator, which is the relative occurrence frequency of the “M” like curves. The relative occurrence frequency of the “M” like curves at a given time index was calculated by the proportion of occurrence of the “M” like curves in the latest three measurements, including the current one. For example, the occurrence frequency at day 0.5 was the
proportion of occurrence of the "M" like curves during day 0.5, day 1.0, and day 2.0. It was calculated as follows:

\[
R_{of} = \frac{\text{Number of 'M' like curves in the latest three measurements}}{3}
\]  

(2)

where \(R_{of}\) denotes the relative occurrence frequency of the "M" like curves.

Based on these definitions, the accurate beginning and ending nodes of the transitioning stages can be given as follows:

1) The beginning of the transitioning stages was defined when the relative occurrence frequency of the "M" like curves was not less than 0.667 for the first time. In other words, the "M" like curves first occurred at least two times in the last three measurements.

2) The ending of the transitioning stages was defined when the relative occurrence frequency of the "M" like curves declined to no more than 0.333. Afterwards, there was no relative occurrence frequency higher than 0.333. Namely, within the agonal stages, the "M" like curves only occurred at most once during any of the last three measurements.

The results of the calculated relative occurrence frequency for the "M" like curves are illustrated in Fig. 3(e2) and Fig. 3(f2).

E. PATHOLOGICAL CAUSES FOR THE OCCURRENCE OF THE "M" LIKE CURVES

In order to explore the specific causes for the occurrence of the "M" like curves within the transitioning stage and to help provide prior medical knowledge for the subsequent therapy of the rescued survivors, another two healthy Beagle dogs (1 female and 1 male) were included in the study. The simulated trapped condition of depriving the dogs of food and water was applied, which is the same condition as that in the previous experiment.

Firstly, it is necessary to verify the regularity of the aforementioned vital states staging method of the transitioning stage. The heart rate, the respiratory rate that were detected by the UWB bio-radar, as well as the temperature and the weight of the latter two dogs, are presented in Fig. 5. The sections within the dashed boxes of the heart rate, as shown in Fig. 5(a) and Fig. 5(b), have much larger values; this is similar to that shown in Fig. 3(a) and Fig. 3(b). As for the respiratory rates shown in Fig. 5(e1) and Fig. 5(f1), the values within the dashed boxes increase sharply; this trend is similar to that shown in Fig. 3(e1) and Fig. 3(f1). In particular, the similar "M" like curves of the respiratory waveforms that were detected by the UWB bio-radar were also observed within this period, as shown in Fig. 6. Therefore, the results in Fig. 5 verified the rationality and regularity of the vital states staging method of the transitioning stage.

Furthermore, it is meaningful to explore the internal pathological causes for the occurrence of the "M" like curves in the transitioning stage. Thus, the simulated trapped condition of the latter two dogs was manually terminated when the dogs entered and were within the transitioning stage. Based on the shape changes of the respiratory waveforms, the increase in the heart rates, as well as the simulated condition of depriving of food and water, we observed the lungs, heart, and stomach. Histopathology diagnosis is a method that is based on the visual examination of the morphology of the histological sections under a microscope. This is achieved by allowing colored histochemical stains to selectively attach to cellular components. It can provide information for diagnosing and characterizing the various pathological conditions.
Lung surfactant, which is assembled and stored in the LBs of the type II alveolar epithelial cells, is the secretion of the alveolar epithelial cells. Slightly swollen, lamellar bodies were fragmented or caved. This finally led to shape changes of respiratory waveforms in the transitioning stage. TEM of the lungs, as illustrated in Fig. 6(b), indicated that infiltrated into the interstitial lung, mainly neutrophils. In Fig. 6(a), indicated that there are a few inflammatory cells. TEM of the lungs found that a small number of inflammatory cells infiltrated into the interstitial lung, mainly neutrophils; (b) TEM of the lungs found that most of the mitochondria in the cytoplasm of type II alveolar epithelial cells were mildly swollen, and most lamellar bodies were fragmented or caved. This finally led to shape changes of respiratory waveforms in the transitioning stage; (c) H&E staining of the stomach found that there were necrosis, nuclear shrinkage, and vacuity of cytoplasm; (d) TEM of the stomach found that most mitochondria were swollen and cytoplasmic contents of some cells were lost; (e) H&E staining of the heart found that a few mitochondria had swelling and some areas of myofibris were wrinkled.

As the welfare and safety of the post-disaster trapped human victims is the ultimate aim of this study, it is crucial to determine whether the dyspnea-related “M” like features identified in the transitioning state of the Beagle dogs have reduced the lung compliance, and prevents alveolar collapse by a surface-area dependent reduction of the alveolar surface tension. Therefore, it is essential for the micromechanics of normal alveoli as well as the lung function.

The fragmentation of the LBs resulted in the insufficiency of the lung surfactant. This increased the alveolar surface tension, reduced the lung compliance, and resulted in alveolar collapse, atelectasis, and dyspnea. Therefore, the pattern of the lung movements changed involuntarily because of the body’s compensating reaction to recover the normal tidal volume. An incomplete breathing movement was added to the breathing cycle. As a result, there was a brief inhalation in the exhaling section, or a temporary exhalation in the inhaling section. Finally, the respiratory waveforms that were detected by the UWB bio-radar displayed “M” like curves. The swelling of most of the mitochondria of the type II alveolar epithelial cells can also harm normal metabolism and function; thus, aggravating the dyspnea. Therefore, the respiratory waveforms that were detected by the UWB bio-radar changed from the normal sine like curves to the “M” like curves, as displayed in Fig. 4. H&E staining and TEM of the stomach, as shown in Fig. 6(c) and Fig. 6(d), determined that the cells experienced necrosis, nuclear shrinkage, vacuity of the cytoplasm, and swelling of most of the mitochondria. The H&E staining results of the heart indicated essentially normal conditions. TEM of the heart, as shown in Fig. 6(e), indicated that a few mitochondria experienced swelling and some of the myofibril areas were wrinkled.

In conclusion, H&E staining and TEM indicated that the lungs and stomach were severely damaged, and the heart was essentially normal. In particular, the damage to the lungs that was mainly caused by the fragmentation of the LBs can lead to the occurrence of “M” like curves for the respiratory waveforms. Based on these prior information of the histopathology diagnosis, surfactant replacement therapy may be a better choice for treating the damaged lungs. In regard to the stomach damage, it was mainly caused by no food and water intake for a long time. The corresponding therapy method may consist of timely injecting nutrients (e.g., glucose solution). These injury pre-diagnoses would save a lot of time for the subsequent therapy after rescuing the survivors. It would enhance the confidence of the medical staff, and finally help save more lives.

**F. RELEVANT ANALOGUE OF THE DYSPNEA-RELATED “M” LIKE FEATURE WITHIN THE DOG’S TRANSITIONING STAGE IN HUMAN SUBJECTS**

As the welfare and safety of the post-disaster trapped human victims is the ultimate aim of this study, it is crucial to determine whether the dyspnea-related “M” like features identified in the transitioning state of the Beagle dogs have
any analogue in the human subjects with dyspnea. NRDS in the human subjects has similar causes to those of the dyspnea-related “M” like curves within the transitioning stage of the dogs. NRDS is a condition of pulmonary deficiency shortly after birth and increases in severity over the first two days of life [35]. It is mainly caused by the insufficiency of lung surfactant, which is similar to the cause for the transitioning stage in the dog subjects. NRDS can also lead to abnormal breathing patterns, known as sobbing respiration or inspiratory retraction [36]. In addition, the respiratory waveforms during sobbing respiration resemble the “M” like curves in the transitioning stage of the dog subjects. This indicates that the experimental results in the animal model of the dog subjects hold important reference values in human subjects. Surfactant replacement therapy and supplemental oxygen are the most widely used treatments for NRDS. The death rate of a neonate with NRDS is the highest on the second day after birth. If the neonate survives for more than three days with appropriate and timely treatment, he/she may exhibit higher lung maturity and a greater hope for recovery.

Because the main cause for both the dyspnea-related “M” like features within the transitioning stage of the dogs and the NRDS in human subjects is the insufficiency of lung surfactant, we believe that the survival time and treatment of the NRDS may serve as references for the trapped victims. If a victim in a disaster is trapped under ruins and cannot obtain any food or water, and the UWB bio-radar identifies “M” like curves in the respiratory waveforms, then the victim can be determined within the transitioning stage. Moreover, the transitioning stage of the victim may not last longer than two days, which can be referred to the highest death rate date for NRDS. Therefore, when the “M” like curves of the respiratory waveforms for trapped human survivors are detected by the UWB bio-radar, time and speed must be given priority to optimize the rescue strategy. At the same time, the signs of the “M” like curves can timely inform the rear graded care center for the preparation of the related medical equipment and medicines for subsequent therapy, such as surfactant replacement therapy and supplemental oxygen. These are the main significances for the welfare and safety of post-disaster trapped human victims in this study.

IV. CONCLUSION
This study aims to promote the welfare and safety of post-disaster trapped human victims. To explore the contactless method of identifying the vital states of the trapped targets, we simulated a post-disaster trapped condition using food and water-deprived Beagle dogs. The respiratory signal detected using a non-contact UWB bio-radar served as the main observing indicator. To reflect and identify the vital states scientifically and objectively, other physiological indicators such as ECG, anal temperature, and weight were recorded through traditional contact measurements. Accordingly, three vital stages were distinguished, namely, normal, transitioning, and agonal stages. The respiratory waveforms obtained from the UWB bio-radar frequently varied from sine like curves to “M” like curves within the transitioning stage. Through histopathology diagnosis, the cause for the occurrence of the “M” like curves was determined to be the insufficiency of lung surfactant due to the fragmentation of LBs within the type II alveolar epithelial cells. The cause for the dyspnea-related “M” like respiratory waveforms within the transitioning stage in the dogs was similar to that for NRDS in the human subjects. Thus, we inferred that the transitioning stage of a trapped survivor without food and water intake may not last longer than two days based on the highest death rate date for NRDS. This information is essential for determining an optimized rescue strategy and for providing timely information for the preparation of related medical equipment and medicines for subsequent therapy.

The novelty of this study lies in the use of only respiratory signals obtained from the non-contact UWB bio-radar to infer the health conditions, life expectancy, and appropriate subsequent treatment of victims in the trapped condition. The study also serves as the foundation for further research. However, the simulated trapped condition in this study only includes the deprivation of food and water. For a further practical application, compound conditions that comprise all other possible trapped situations, such as confined spaces, compression fracture due to ruins, and bleeding, should be simulated.

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REFERENCES
[1] F. Fiedrich, F. Gehbauer, and U. Rickers, “Optimized resource allocation for emergency response after earthquake disasters,” Saf. Sci., vol. 35, nos. 1–3, pp. 41–57, Jun. 2000.
[2] N. Altyay and W. G. Green, III, “OR/MS research in disaster operations management,” Eur. J. Oper. Res., vol. 175, no. 1, pp. 475–493, 2006.
[3] X. Hui and E. C. Kan, “No-touch measurements of vital signs in small conscious animals,” Sci. Adv., vol. 5, no. 2, Feb. 2019, Art. no. eaau0169.
[4] C. Li and J. Lin, Microwave Noncontact Motion Sensing and Analysis. Hoboken, NJ, USA: Wiley, 2014.
[5] C. Li, Z. Peng, T.-Y. Huang, T. Fan, F.-K. Wang, T.-S. Hong, J.-M. Munoz-Ferreras, R. Gomez-Garcia, L. Ran, and J. Lin, “A review on recent progress of portable short-range noncontact microwave radar systems,” IEEE Trans. Microw. Theory Techn., vol. 65, no. 5, pp. 1692–1706, May 2017.
[6] Y. Zhang, F. Qi, L. Lv, F. Liang, and J. Wang, “Bioradar technology: Recent research and advancements,” IEEE Microw. Mag., vol. 20, no. 8, pp. 58–73, Aug. 2019.
[7] H. Hong, L. Zhang, H. Zhao, H. Chu, C. Gu, M. Brown, X. Zhu, and C. Li, “Microwave sensing and sleep: Noncontact sleep-monitoring technology with microwave biomedical radar,” IEEE Microw. Mag., vol. 20, no. 8, pp. 18–29, Aug. 2019.
[8] F. Khan, A. Ghaffar, N. Khan, and S. H. Cho, “An overview of signal processing techniques for remote health monitoring using impulse radio UWB transceiver,” Sensors, vol. 20, no. 9, p. 2479, Apr. 2020.
[9] X. Yang, X. Zhang, H. Qian, Y. Ding, and L. Zhang, “MMT-HEAR: Multiple moving targets heartbeats estimation and recovery using IR-UWB radars,” in Proc. 42nd Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC), Montreal, QC, Canada, Jul. 2020, pp. 5733–5736.
[10] A. Cazzorla, G. De Angelis, A. Moschitta, M. Dionigi, F. Alimenti, and P. Cardone, “A 5.6-GHz UWB position measurement system,” IEEE Trans. Instrum. Meas., vol. 62, no. 3, pp. 675–683, Mar. 2013.

[11] A. R. Jimenez Ruiz and F. Seco Granja, “Comparing ubiquitous, BeSpoon, and DecaWave UWB location systems: Indoor performance analysis,” IEEE Trans. Instrum. Meas., vol. 66, no. 8, pp. 2106–2117, Aug. 2017.

[12] Y. Ma, F. Liang, P. Wang, H. Lv, X. Yu, Y. Zhang, and J. Wang, “An accurate method to distinguish between stationary human and dog targets under through-wall condition using UWB radar,” Remote Sens., vol. 11, no. 21, p. 2571, Nov. 2019.

[13] Y. Wang, X. Yu, Y. Zhang, H. Lv, T. Jiao, G. Gu, W. Z. Li, Z. Li, X. Jing, and J. Wang, “Using wavelet entropy to distinguish between humans and dogs detected by UWB radar,” Prog. Electromagn. Res., vol. 139, pp. 335–352, 2013.

[14] H. K. Tiwari, P. R. P. Verma, T. Monif, R. Arora, and S. Reyar, “Preliminary investigation of posture monitoring applications for analytical transmission electron microscopy,” in Proc. Photon. Electromagn. Res. Symp. Fall (PIERS-Fall), Xiamen, China, 2019, pp. 118–121, Jun. 2015.

[15] P. Wang, Y. Zhang, Y. Ma, F. Liang, Q. An, H. Xue, X. Yu, H. Lv, and J. Wang, “Method for distinguishing humans and animals on vital signs monitoring using IR-UWB radar,” Int. J. Environ. Res. Public Health, vol. 16, no. 22, p. 4462, Nov. 2019.

[16] G. P. Moberg, The Biology of Animal Stress: Basic Principles and Implications for Animal Welfare. New York, NY, USA: CABIL, 2000.

[17] K. C. Aske and C. A. Waugh, “Expanding the 3R principles: More rigour and transparency in research using animals,” EMBO Rep., vol. 18, no. 9, pp. 1490–1492, Jul. 2017.

[18] P. Wang, Y. Ma, F. Liang, Y. Zhang, X. Yu, Z. Li, Q. An, H. Lv, and J. Wang, “Non-contact vital signs monitoring of dog and cat using a UWB radar,” Animals, vol. 10, no. 2, p. 205, Jan. 2020.

[19] N. Gurel, K. Granhaug, J. A. Michaeelsen, S. Bagga, H. A. Hjortland, M. R. Knutsen, T. S. Lange, and D. T. Wisland, “A 118-mW pulse-based radar SoC in 55-nm CMOS for non-contact human vital signs detection,” IEEE J. Solid-State Circuits, vol. 52, no. 12, pp. 3421–3433, Dec. 2017.

[20] P. Maud, O. Thavarak, L. Cédrick, B. Michèle, B. Vincent, P. Olivier, and B. Régis, “Evidence for the use of isoflurane as a replacement for chloral hydrate anesthesia in experimental stroke: An ethical issue,” BioMed Res. Int., vol. 2014, p. 802539.

[21] X.-Y. Wu, Y.-T. Hu, L. Guo, J. Lu, Q.-B. Zhu, E. Yu, J.-L. Wu, L.-G. Shi, M.-L. Huang, and A.-M. Bao, “Effect of pentobarbital and isoflurane on acute stress response in rat,” Physiol. Behav., vol. 145, pp. 118–121, Jun. 2015.

[22] D. C. Warltier and P. S. Pagel, “Cardiovascular and respiratory actions of desflurane: Is desflurane different from isoflurane?” Anesthesia Analgesia, vol. 75, no. 4, pp. S17–S29, Oct. 1992.

[23] Y. Ma, F. Liang, P. Wang, Y. Yin, Y. Zhang, and J. Wang, “Research on identifying different life states based on the changes of vital signs of rabbit under water and food deprivation by UWB radar measurement,” in Proc. Photon. Electromagn. Res. Symp. Fall (PIERS-Fall), Xiamen, China, Dec. 2019, pp. 397–403.

[24] B. Ehteshami Bejnordi, G. Litjens, N. Timofeeva, I. Otte-Holler, D. C. Warltier, and P. S. Pagel, “Cardiovascular and respiratory actions of desflurane: Is desflurane different from isoflurane?” Anesthesia Analgesia, vol. 119, no. 7, pp. 1676–1695, Aug. 2009.

[25] Y. Ma, F. Liang, P. Wang, Y. Yin, Y. Zhang, and J. Wang, “Research on identifying different life states based on the changes of vital signs of rabbit under water and food deprivation by UWB radar measurement,” in Proc. Photon. Electromagn. Res. Symp. Fall (PIERS-Fall), Xiamen, China, Dec. 2019, pp. 397–403.
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