Accurate Respiration Measurement Using DC-Coupled Continuous-Wave Radar Sensor for Motion-Adaptive Cancer Radiotherapy

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Abstract—Accurate respiration measurement is crucial in motion-adaptive cancer radiotherapy. Conventional methods for respiration measurement are undesirable because they are either invasive to the patient or do not have sufficient accuracy. In addition, measurement of external respiration signal based on conventional approaches requires close patient contact to the physical device which often causes patient discomfort and undesirable motion during radiation dose delivery. In this paper, a dc-coupled continuous-wave radar sensor was presented to provide a noncontact and noninvasive approach for respiration measurement. The radar sensor was designed with dc-coupled adaptive tuning architectures that include RF coarse-tuning and baseband fine-tuning, which allows the radar sensor to precisely measure movement with stationary moment and always work with the maximum dynamic range. The accuracy of respiration measurement with the proposed radar sensor was experimentally evaluated using a physical phantom, human subject, and moving plate in a radiotherapy environment. It was shown that respiration measurement with radar sensor while the radiation beam is on is feasible and the measurement has a submillimeter accuracy when compared with a commercial respiration monitoring system which requires patient contact. The proposed radar sensor provides accurate, noninvasive, and noncontact respiration measurement and therefore has a great potential in motion-adaptive radiotherapy.

Index Terms—Cancer radiotherapy, dc information, dc offset, moving tumor, radar, respiration.
it better than the existing contact devices that are sensitive to the surrounding environment. In radar respiration measurement, the radar sensor suffers from dc offset at the RF front-end output, which is mainly caused by the reflections from stationary objects surrounding the body. The dc offset may saturate or limit the dynamic range of the following stages of baseband amplifiers. To overcome this demerit, ac coupling has been commonly used in radar sensors. However, due to the high-pass characteristics of the coupling capacitor, ac coupling leads to significant signal distortion when the target motion has a very low frequency or a dc component. Respiration is such a motion that is low frequency of less than 0.5 Hz and tends to rest for a while at the end of expiration (EOE), i.e., there is a short stationary moment after lung deflation. This is a problem in radar respiration measurement. To deal with it, several approaches, such as high RF-LO isolation mixers [8], have been introduced to employ dc coupling in radar sensors. However, these approaches are either cumbersome to implement or do not completely remove dc offsets and limit the dynamic range of the baseband amplifiers.

In this paper, a dc-coupled CW radar sensor was presented to provide a noncontact and noninvasive approach for accurate respiration measurement. The radar sensor was designed with dc-coupled adaptive tuning architectures that include RF coarse-tuning and baseband fine-tuning. The RF tuning was implemented using a path of an attenuator and a phase shifter at the RF front end of the radar sensor [9], [10]. It adds a portion of the transmitter signal to the receiver signal to cancel out most of the dc offset. To further calibrate the remaining dc offset, the baseband fine-tuning architecture was used to adaptively adjust the amplifier bias to the desired level that allows both high gain amplification and maximum dynamic range at the baseband stage. With the aforementioned dc tuning architectures, the radar sensor is able to precisely measure the low-frequency respiration motions with stationary moment. The radar sensor was tested in the lab environment to demonstrate its ability of accurate displacement measurement that preserves dc information of stationary moment. Moreover, the radar sensor was integrated and tested with the linear accelerator (LINAC) to validate its clinical use. In order to achieve accurate radiation beam targeting using respiration measurement, a correlation model needs to be built and validated between the internal tumor target and external respiration signal. This can be decoupled and is generally treated as a separate issue from respiration measurement. In fact, various approaches have been explored to infer the internal target position from external measurement [11], [12]. Therefore, this study has focused on the accurate measurement of respiration in a noninvasive and noncontact way.

The radar motion-adaptive radiotherapy system will be introduced in Section II. Section III discusses the dc-coupled radar sensor with tuning architectures. Experimental evaluations would be presented in Section IV. A conclusion will be drawn in Section V.

II. RADIOThERAPY SYSTEM WITH Radar SENSING

The motion-adaptive radiotherapy system based on radar respiration sensing is shown in Fig. 1. The radiotherapy process includes two steps: treatment preparation, which consists of patient simulation and treatment planning, and treatment execution, which delivers radiation dose to the patient. At the patient simulation stage, the patient and tumor geometrical information is collected through computed tomography (CT) scan and then a 3-D patient model is built for the target tumor and organs at risk [1], [2]. The patient’s breathing pattern is also examined at this stage. Those patients who cannot exhibit stable breathing patterns would be excluded from the motion-adaptive radiotherapy. Treatment planning is a virtual process that designs the patient treatment using the patient model built at the simulation stage. During the radiotherapy execution stage, a medical LINAC would be working together with two radar sensors that dynamically monitor the chest wall and the abdomen to provide the real-time motion information. The LINAC could also be integrated with a radar sensor having beam-scanning capability, shown as inset (b) in Fig. 1, which makes it possible to use one radar sensor to simultaneously measure the breathing motions at multiple body locations [13]. In the third step, the advanced tumor tracking algorithm combines the chest wall and abdomen motion information together with the precollected patient model to extract the tumor locations in real time. Then, a controller utilizes the extracted tumor location information to control the LINAC to either perform gated radiotherapy or steer the radiation beam to track the tumor. The inset (c) shows the designed 2.4-GHz miniature radar sensor with the size of 5 cm × 5 cm. The radar sensor was configured with a ZigBee module for wireless data transmission, which allows wireless monitoring of the respiration outside the treatment room and relieves from a bunch of cables that may constrain the radar installation to the LINAC. The radar sensor will be working in the arctangent-demodulated microwave
the laptop configures the power supply channel, for example, assuming that the amplifier
V_{\text{OUT}}$ are dynamically read by $Q_i$ when the output is close to the $\pm$ biasing voltage $V_T, Q_i$ are the dc offsets of the differential channels, and $V_0$ is the tuning voltage from the power supply, $\frac{R_2}{R_1}$ is the tuning path that allows both high gain amplification and maximum dynamic range. As shown in Fig. 3, unlike the conventional ac-coupled radar sensor biased at a fixed dc point, the proposed baseband fine-tuning architecture allows the external power supply to adjust just the biasing level at the baseband amplifier. The baseband amplifiers’ outputs $V_{Q_{\text{OUT}}}/V_{I_{\text{OUT}}}$ are dynamically read by the microcontroller (TI MSP430) that transmits the digitized data via a ZigBee node to another node connected to the laptop. Take the $Q$ channel, for example, assuming that the amplifier has infinite open-loop gain, the dc level of the amplifier output is

$$V_{Q_{\text{OUT}}} = V_T, Q_i + \frac{R_2}{R_1} (V_Q^+ - V_Q^-)$$  

where $V_T, Q_i$ is the tuning voltage from the power supply, $V_Q^+$ and $V_Q^-$ are the dc offsets of the differential channels, and $\frac{R_2}{R_1}$ is the closed-loop gain. Depending on the $V_{Q_{\text{OUT}}}/V_{I_{\text{OUT}}}$, the laptop configures the power supply (Tektronics PS2521G), through a GPIB interface, to increase the biasing voltage $V_T, Q_i/V_{I, J}$ when the output is close to the lower rail, or decrease it when the output is close to the upper rail. This process continues until the amplifier output reaches the desired dc level that allows both high-gain application and maximum dynamic range. The GPIB interface can be removed after the dc tuning process is finished. A wireless tuning loop is also possible by using the ZigBee communications.

Experiments were carried out to validate the dc calibration capability of the proposed dc-coupled radar sensor. In the first experiment, the RF coarse-tuning loop was verified to remove most of the dc offset and the voltage level for the baseband fine-tuning. As shown in Fig. 4, the original dc difference of the differential $Q$ channel at the mixer output was 0.07 V.
Assume that the baseband amplifier works with a gain of 200, which is necessary to boost the radar signals that are usually very weak, the amplifier dc output results in 14 V, which saturates the amplifier since the dc level is actually way above the amplifier power supply of 3.3 V. To adjust it to half of the power supply, baseband fine-tuning would need $V_{T,Q} = -12.35 \text{ V}_{\text{DC}}$ to be applied to the amplifier, as shown in (1). The high tuning voltage may potentially damage the baseband amplifier. However, after RF coarse-tuning, the dc difference drops significantly to 0.005 V. In this case, the baseband fine-tuning only needs $V_{T,Q} = 0.65 \text{ V}_{\text{DC}}$ to pull the amplifier dc output to the desired level. In the second experiment, the two tuning architectures were combined to validate the dc calibration functionality. Fig. 5 shows the dc offset tuning process. It is seen that both $I/Q$ channels were originally at the lower end of the amplifier power supply rails. The coarse-tuning architecture was used to adaptively pull up the $I/Q$ channels step-by-step to reasonable levels that allow further baseband fine-tuning. It should be known that the RF output $I/Q$ channels are 90° out of phase, and the coarse-tuning cannot compensate for the phase offset for both channels at the same time. After coarse-tuning, the fine-tuning feedback loop precisely adjusts the $I/Q$ dc offsets to the desired levels, with a fine step of 0.01 V, owing to the high resolution of the power supply. In Fig. 5, the baseband amplifiers’ outputs were precisely tuned to 1.65 V, which is half way between the baseband amplifier supply rails, so that the maximum dynamic range is guaranteed. It should be noted that in real application, the tuning procedure can be made very fast (within a few milliseconds). Fig. 6 shows the radar measurement results before and after a fast dc tuning. It is seen that the amplifier was originally affected by large dc offset such that the $Q$ channel was totally saturated on the top and the $I$ channel was partially clamped on the bottom. However, after dc tuning, both channels exhibit satisfactory amplification on signals. The $I/Q$ channels have different amplitudes due to the different residual phase [16].

The proposed dc-coupled radar sensor is able to measure target motions with stationary moment. That is, it can preserve the dc information of the stationary moment. It can also preserve the dc information that comes from the nonlinear cosine expansion, which is necessary for accurate arctangent demodulation. In a word, owing to the all-pass characteristic of the dc-coupled structure, the proposed radar sensor is able to maintain the signal integrity by preserving all the dc information. In Fig. 7, the ac-coupled radar and the dc-coupled radar were used to measure the same sinusoidal motion of an actuator. The measurement results are shown in a constellation graph to compare the $I/Q$ trajectories. It is seen that the trajectory of the dc-coupled radar matches well with the unit circle, while the ac-coupled radar tends to deviate from the circular arc to form a ribbon-like shape. This is because of the radar signal amplitude variation that is caused by the ac coupling capacitors’ charging and discharging. Since the dc-coupled radar has a trajectory that is much closer to an ideal arc, it can be used for more accurate dc calibration [17], and therefore leads to more accurate arctangent demodulation.
verify the dc-coupled radar’s ability to preserve the dc information of stationary moment, both the dc radar and ac radar were used to measure the actuator that was programmed to move sinusoidally but with a stationary moment between two adjacent cycles. The measurement results were shown in Fig. 8. It is seen that the dc-coupled radar successfully preserves the stationary information by precisely matching with the programmed actuator motion. However, the ac radar measured movement starts to deviate from the ground truth when the stationary moment begins. This is because the ac coupling capacitors cannot hold the charge for a long time and they tend to discharge over the stationary moment. The proposed dc-coupled radar sensor is expected to more precisely measure the respiration motion that has very low frequency and has a short stationary moment during its cycle.

IV. EXPERIMENTAL EVALUATIONS AND DISCUSSIONS

The accuracy of the proposed dc-coupled radar sensor for respiration measurement has been evaluated with physical experiments in a radiotherapy environment. During the experiments, the radar sensor was placed on the fixation frame crossed over the treatment platform, as shown in Fig. 9. The respiration data were wirelessly transmitted to a ZigBee receiver end connected to the laptop that was placed outside the treatment room.

Three experiments were carried out to validate the use of radar respiration sensing for clinical applications in radiotherapy. First, a physical motion phantom performed a sinusoidal-like movement with a ∼5-s period during each cycle. The radar sensor and the real-time position management (RPM) system (Varian Medical Systems, Palo Alto, CA) were used to measure the same motion phantom on the treatment platform. The RPM system is a widely used respiration monitoring approach in radiotherapy, which employs an infrared camera to track an external reflective marker put on the patient’s chest or abdomen. An infrared marker was put on top of the phantom in order for the RPM system to track its motion. The infrared camera was mounted on the wall and is in the line of sight of the marker.

This experiment evaluated the accuracy performance of the radar sensor. The setup of this test is shown in Fig. 9(a). To simulate the real clinical situation, the treatment radiation was turned on during the phantom test. Under some ideal situations, the RPM system using an infrared camera and reflective marker can provide accurate measurement of respiratory signal of a single point, and thus was used as the gold standard to assess the performance of our radar sensor. However, because of the complexity of human respiration, the internal tumor location cannot be de-
This requires simultaneous measurement of multiple external surrogates, which can be achieved by our radar system. In the second experiment, a human subject laid on the treatment platform to simulate the patient’s respiration. The setup is shown in Fig. 9(b). In the third experiment, to further account for the clinically relevant breathing patterns, the Respiratory Gating Platform (Standard Imaging, Middleton, WI) was used to simulate breathing motions with various amplitudes and periods. The Respiratory Gating Platform simulates breathing motions for training, quality assurance, and dose verification in radiotherapy. Radar measured the different motion patterns during the experiment. The setup is shown in Fig. 9(c).

The measurement results are illustrated in Fig. 10 for the phantom case. It is seen that the radar sensor measurement matches very well with that from the RPM system. This demonstrates that the proposed radar sensor is not interfered by the high-energy radiation dose and can work compatibly with the LINAC during the radiation dose delivery process. For the experiment on the human subject, the radar measured respiration is shown in Fig. 11(a). The subject was coached to dynamically adjust his breathing to put the EOE position within the shaded area, so as to generate reproducible respiration signals, from which, gating signals would be easy to be obtained. The accurate measurement of the dc-coupled radar sensor also allows the coaching reference area to be chosen near the position of end of inspiration (EOI), depending on specific clinical situations. The radar measured reproducible respiration signals allow both amplitude gating and phase gating [18]. The red line in Fig. 11(a) shows the reference for amplitude gating. The respiration signal triggers the radiation on once its amplitude falls below the reference line. Fig. 11(b) shows the gating signals with a duty cycle of 40.5%. For the Respiratory Gating Platform measurement, the radar measured data are shown in Fig. 12. The platform was configured to move at amplitudes of 5, 10, and 20 mm, and with periods of 4, 5, and 6 s, respectively. These motion patterns represent the common breathing parameters in the clinical radiotherapy. It is seen that the radar sensor was able to accurately capture all the respiration motion patterns with various amplitudes and periods. The radar measurement accuracy for various motion patterns is illustrated in Table I. The RMS error was obtained by comparing the radar measured movement with the actual motion pattern of the gating platform. The measurement error is mainly due to the radar system noise, such as quantization noise, electronic noise, and environmental noise, which introduces variations to the measured signal. However, even with noise, it is shown that the proposed radar sensor has a submillimeter measurement accuracy.

<table>
<thead>
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<th>Amplitude [mm]</th>
<th>Period [second]</th>
<th>RMS Err. [mm]</th>
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<td>20</td>
<td>4</td>
<td>0.202</td>
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<td></td>
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<td></td>
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<td>0.091</td>
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Fig. 10. Phantom motion measured by radar with the LINAC radiation beam turned on, compared with the same phantom motion measured by Varian’s RPM system.

Fig. 11. (a) Radar measured respiration signal. (b) Generated gating signal. The shaded area indicates the coach reference area, and the red line represents the reference for gating.

Fig. 12. Radar measured gating platform motions with amplitudes of 20, 10, and 5 mm, and periods of (a) 4 s, (b) 5 s, and (c) 6 s.
The proposed radar sensor system has the potential application of real-time tumor tracking for motion-adaptive radiotherapy [3]. As mentioned in Section II, respiratory gating has to leverage the tradeoff between duty cycle and residual tumor motion. However, this demerit is eliminated in the tumor tracking type of treatment, in which, the radiation beam is always on and dynamically follows the moving tumor in real time, as shown in Fig. 2(b). It is technologically more challenging than respiratory gating treatments. For radiotherapy treatments based on LINACs, tumor tracking can be implemented by tracking the tumor motion using a dynamic multileaf collimator that shapes the radiation beam [3]. In order for the radiation beam to dynamically follow the tumor, the location of the tumor must be known with high accuracy and in real time. Finding the accurate tumor location from external respiration measurement is currently an active research topic [11] and is beyond the scope of this paper.

V. Conclusion

A dc-coupled CW radar sensor has been presented to provide a noncontact and noninvasive approach for accurate respiration measurement in motion-adaptive radiotherapy. The proposed radar sensor is configured with adaptive dc tuning architectures and able to precisely measure movements with stationary moment, such as the respiration motion. The concept of a radiotherapy system with radar sensing has been introduced and described in the context of respiratory gating and tumor tracking for motion-adaptive radiotherapy. The dc-coupled CW radar sensor was designed and its dc tuning capability was tested. Experiments were carried out to validate the radar sensor for measuring movements with stationary moment. The accuracy of respiration measurement using dc-coupled radar sensor has been experimentally evaluated using both physical phantom and human subject in a radiotherapy environment. It has been shown that respiration measurement with radar sensor while the radiation beam is on is feasible and the measurement has a submillimeter accuracy when compared with the commercial Respiratory Gating Platform. The proposed radar sensor provides accurate, noninvasive, and noncontact respiration measurement and therefore has a great potential in motion-adaptive radiotherapy.

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REFERENCES

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Index Terms—Cancer radiotherapy, dc information, dc offset, moving tumor, radar, respiration.

I. INTRODUCTION

CANCER is the second leading cause of deaths in the U.S. According to the American Cancer Society, 1.6 million new cancer cases will be diagnosed and about 600 000 people will die from the disease in 2012. Radiation therapy is a major modality for treating cancer patients. Studies have shown that an increased radiation dose to the tumor will lead to improved local control and survival rates. However, in many anatomic sites (e.g., lung and liver), the tumors can move significantly (~2–3 cm) with respiration. The respiratory tumor motion has been a major challenge in radiotherapy to deliver sufficient radiation dose without causing secondary cancer or severe radiation damage to the surrounding healthy tissue [1], [2].

Motion-adaptive radiotherapy explicitly accounts for and tackles the issue of tumor motion during radiation dose delivery, in which respiratory gating and tumor tracking are two promising approaches. Respiratory gating limits radiation exposure to a portion of the breathing cycle when the tumor is in a predefined gating window [3]. Tumor tracking, on the other hand, allows continuous radiation dose delivery by dynamically adjusting the radiation beam so that it follows the real-time tumor movement. For either technique to be effective, accurate measurement of the respiration signal is required. Conventional methods for respiration measurement are undesirable because they are either invasive to the patient or do not have sufficient accuracy. For instance, measurement based on fiducial markers requires an invasive implantation procedure and involves serious risks to the patient, e.g., pneumothorax for lung cancer patients [4]. On the other hand, measurement of external respiration surrogates using infrared reflective marker, spirometer, or pressure belt etc., generally lacks sufficient accuracy to infer the internal tumor position, because they only provide a point measurement or a numerical index of the respiration [5]. In addition, these devices have to be in close contact with the patient in order to function. This often brings discomfort to the patient and can lead to additional patient motion during dose delivery. To that end, accurate respiration measurement that does not require invasive procedures or patient contact is urgently needed in order to realize the potential of motion-adaptive radiotherapy.

Continuous-wave (CW) radar sensor provides a noncontact and noninvasive approach for respiration measurement [6], [7]. Instead of measuring the marker, it directly measures the periodic motion of the body, which has better correlation with the lung tumor motion. Moreover, the radar system is insensitive to clothing and chest hair, due to microwave penetration, making
it better than the existing contact devices that are sensitive to the surrounding environment. In radar respiration measurement, the radar sensor suffers from dc offset at the RF front-end output, which is mainly caused by the reflections from stationary objects surrounding the body. The dc offset may saturate or limit the dynamic range of the following stages of baseband amplifiers. To overcome this demerit, ac coupling has been commonly used in radar sensors. However, due to the high-pass characteristics of the coupling capacitor, ac coupling leads to significant signal distortion when the target motion has a very low frequency or a dc component. Respiration is such a motion that is low frequency of less than 0.5 Hz and tends to rest for a while at the end of expiration (EOE), i.e., there is a short stationary moment after lung deflation. This is a problem in radar respiration measurement. To deal with it, several approaches, such as high RF-LO isolation mixers [8], have been introduced to employ dc coupling in radar sensors. However, these approaches are either cumbersome to implement or do not completely remove dc offsets and limit the dynamic range of the baseband amplifiers.

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is the tuning voltage from the power supply, 

\[ V_{\text{T},Q} = \frac{R^2}{R_1} (V_Q^+ - V_Q^-) \]  

(1)

where \( V_{\text{T},Q} \) is the tuning voltage from the power supply, \( V_Q^+ \) and \( V_Q^- \) are the dc offsets of the differential channels, and \( R^2/R_1 \) is the closed-loop gain. Depending on the dc value of \( V_{\text{Q},\text{OUT}}/V_{\text{T},\text{OUT}} \), the laptop configures the power supply (Tektronics PS2521G), through a GPIB interface, to increase the biasing voltage \( V_{\text{T},Q}/V_{\text{T},J} \) when the output is close to the lower rail, or decrease it when the output is close to the upper rail. This process continues until the amplifier output reaches the desired dc level that allows both high-gain application and maximum dynamic range. The GPIB interface can be removed after the dc tuning process is finished. A wireless tuning loop is also possible by using the ZigBee communications.

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Fig. 6. Radar measurement result before and after dc tuning.

Fig. 7. Constellation graph of the signals measured by ac radar and dc radar. Insets show the time-domain radar signals.

Fig. 8. Programmed actuator movement compared with the movements measured by ac-coupled radar and dc-coupled radar in an electronic lab.

IV. EXPERIMENTAL EVALUATIONS AND DISCUSSIONS

The accuracy of the proposed dc-coupled radar sensor for respiration measurement has been evaluated with physical experiments in a radiotherapy environment. During the experiments, the radar sensor was placed on the fixation frame crossed over the treatment platform, as shown in Fig. 9. The respiration data were wirelessly transmitted to a ZigBee receiver end connected to the laptop that was placed outside the treatment room.

Three experiments were carried out to validate the use of radar respiration sensing for clinical applications in radiotherapy. First, a physical motion phantom performed a sinusoidal-like movement with a \( \sim 5 \) s period during each cycle. The radar sensor and the real-time position management (RPM) system (Varian Medical Systems, Palo Alto, CA) were used to measure the same motion phantom on the treatment platform. The RPM system is a widely used respiration monitoring approach in radiotherapy, which employs an infrared camera to track an external reflective marker put on the patient’s chest or abdomen. An infrared marker was put on top of the phantom in order for the RPM system to track its motion. The infrared camera was mounted on the wall and is in the line of sight of the marker. This experiment evaluated the accuracy performance of the radar sensor. The setup of this test is shown in Fig. 9(a). To simulate the real clinical situation, the treatment radiation was turned on during the phantom test. Under some ideal situations, the RPM system using an infrared camera and reflective marker can provide accurate measurement of respiratory signal of a single point, and thus was used as the gold standard to assess the performance of our radar sensor. However, because of the complexity of human respiration, the internal tumor location cannot be de-
arrived from only a point measurement with sufficient accuracy. This requires simultaneous measurement of multiple external surrogates, which can be achieved by our radar system. In the second experiment, a human subject laid on the treatment platform to simulate the patient’s respiration. The setup is shown in Fig. 9(b). In the third experiment, to further account for the clinically relevant breathing patterns, the Respiratory Gating Platform (Standard Imaging, Middleton, WI) was used to simulate breathing motions with various amplitudes and periods. The Respiratory Gating Platform simulates breathing motions for training, quality assurance, and dose verification in radiotherapy. Radar measured the different motion patterns during the experiment. The setup is shown in Fig. 9(c).

The measurement results are illustrated in Fig. 10 for the phantom case. It is seen that the radar sensor measurement matches very well with that from the RPM system. This demonstrates that the proposed radar sensor is not interfered by the high-energy radiation dose and can work compatibly with the LINAC during the radiation dose delivery process. For the experiment on the human subject, the radar measured respiration is shown in Fig. 11(a). The subject was coached to dynamically adjust his breathing to put the EOE position within the shaded area, so as to generate reproducible respiration signals, from which, gating signals would be easy to be obtained. The accurate measurement of the dc-coupled radar sensor also allows the coaching reference area to be chosen near the position of end of inspiration (EOI), depending on specific clinical situations. The radar measured reproducible respiration signals allow both amplitude gating and phase gating [18]. The red line in Fig. 11(a) shows the reference for amplitude gating. The respiration signal triggers the radiation on once its amplitude falls below the reference line. Fig. 11(b) shows the gating signals with a duty cycle of 40.5%. For the Respiratory Gating Platform measurement, the radar measured data are shown in Fig. 12. The platform was configured to move at amplitudes of 5, 10, and 20 mm, and with periods of 4, 5, and 6 s, respectively. These motion patterns represent the common breathing parameters in the clinical radiotherapy. It is seen that the radar sensor was able to accurately capture all the respiration motion patterns with various amplitudes and periods. The radar measurement accuracy for various motion patterns is illustrated in Table I. The RMS error was obtained by comparing the radar measured movement with the actual motion pattern of the gating platform. The measurement error is mainly due to the radar system noise, such as quantization noise, electronic noise, and environmental noise, which introduces variations to the measured signal. However, even with noise, it is shown that the proposed radar sensor has a submillimeter measurement accuracy.

### TABLE I

<table>
<thead>
<tr>
<th>Amplitude [mm]</th>
<th>Period [second]</th>
<th>RMS Err. [mm]</th>
</tr>
</thead>
<tbody>
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<td>20</td>
<td>4</td>
<td>0.202</td>
</tr>
<tr>
<td></td>
<td>5</td>
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<tr>
<td></td>
<td>5</td>
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<tr>
<td></td>
<td>6</td>
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</tr>
<tr>
<td>5</td>
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<td></td>
<td>6</td>
<td>0.115</td>
</tr>
</tbody>
</table>

Fig. 10. Phantom motion measured by radar with the LINAC radiation beam turned on, compared with the same phantom motion measured by Varian’s RPM system.

Fig. 11. (a) Radar measured respiration signal. (b) Generated gating signal. The shaded area indicates the coach reference area, and the red line represents the reference for gating.

Fig. 12. Radar measured gating platform motions with amplitudes of 20, 10, and 5 mm, and periods of (a) 4 s, (b) 5 s, and (c) 6 s.
The proposed radar sensor system has the potential application of real-time tumor tracking for motion-adaptive radiotherapy [3]. As mentioned in Section II, respiratory gating has to leverage the tradeoff between duty cycle and residual tumor motion. However, this demerit is eliminated in the tumor tracking type of treatment, in which, the radiation beam is always on and dynamically follows the moving tumor in real time, as shown in Fig. 2(b). It is technologically more challenging than respiratory gating treatments. For radiotherapy treatments based on LINACs, tumor tracking can be implemented by tracking the tumor motion using a dynamic multileaf collimator that shapes the radiation beam [3]. In order for the radiation beam to dynamically follow the tumor, the location of the tumor must be known with high accuracy and in real time. Finding the accurate tumor location from external respiration measurement is currently an active research topic [11] and is beyond the scope of this paper.

V. CONCLUSION

A dc-coupled CW radar sensor has been presented to provide a noncontact and noninvasive approach for accurate respiration measurement in motion-adaptive radiotherapy. The proposed radar sensor is configured with adaptive dc tuning architectures and able to precisely measure movements with stationary moment, such as the respiration motion. The concept of a radiotherapy system with radar sensing has been introduced and described in the context of respiratory gating and tumor tracking for motion-adaptive radiotherapy. The dc-coupled CW radar sensor was designed and its dc tuning capability was tested. Experiments were carried out to validate the radar sensor for measuring movements with stationary moment. The accuracy of respiration measurement using dc-coupled radar sensor has been experimentally evaluated using both physical phantom and human subject in a radiotherapy environment. It has been shown that respiration measurement with radar sensor while the radiation beam is on is feasible and the measurement has a submillimeter accuracy when compared with the commercial Respiratory Gating Platform. The proposed radar sensor provides accurate, noninvasive, and noncontact respiration measurement and therefore has a great potential in motion-adaptive radiotherapy.

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REFERENCES