A Minimally Invasive Robotic Tissue Palpation Device for Intra-Operative Detection of Lung Nodules

Objective: To evaluate the efficacy of a robotic palpation device in the detection of lung nodules during robot-assisted minimally invasive surgery.

Methods: The robotic palpation device was constructed by mounting a deployable stiffness measurement sensing probe on the tip of a custom-built wire-driven steerable catheter. The sensing probe consisted of a thin film-based force sensor (diameter: 3 mm; UNEO), two spiral-headed pogo pins as contact electrodes (diameter: 1 mm, MilMax), and a rigid hemispheric compression head made of acrylic plastic (radius: 2.5 mm). A motion control module that enabled multi-directional device movements, such as linear displacement, rotation, and deflection, was integrated in the device to guide the sensing probe to the target tissue surface. Two cancer models were generated to mimic a nodule surrounded by healthy tissue. In the first model, an Indocyanine Green (ICG)-labeled cylindrical-shaped silicone (ratio of prepolymer to crosslinker: 10:1; diameter: 12 mm; thickness: 2.5 mm), which recapitulated a stiff nodule, was embedded at the center of a soft gelatin block (concentration: 10% w/v; length: 35 mm, width: 35 mm, thickness: 10 mm). The second model was generated by making an incision in the distal region of a freshly isolated swine lung and inserting an ICG-labelled silicone (diameter: 2 cm) into the subpleural region, approximately 5 mm below the pleura surface. The incised area was then sutured (4-0 silk) to prevent air leak and lung collapse.

Results: The robotic palpation device was designed to intra-operatively and non-destructively quantify the stiffness of the soft tissues by determining the elastic modulus (E) (Fig. 1A-1C). We first investigated whether the palpation device can accurately profile the stiffness of gelatin-based phantoms containing a nodule mimic (Fig. 1D). The generated stiffness map showed that while E values at peripheral areas of the phantom block varied between 23 to 27 kPa, there was a substantial increase in the E values (range: 38 to 50 kPa) at the center of the tissue phantom where the silicone-based nodule was located (Fig. 1E). Further, we evaluated a lung cancer model that mimicked the presence of small nodule (size: 2 cm) in the distal regions of the lungs to determine whether our palpation device can accurately discriminate the nodule from healthy tissue (Fig. 1F). Notably, the generated stiffness map revealed that the E values ranged from 9.3 to 28.3 kPa, where the stiffness of 28.3 kPa corresponded to the precise location of the nodule in the lung lobe (Fig. 1G).

Conclusion: Overall, this study highlights the potential of a novel robotic palpation device as an intraoperative tool to assess and localize pathologic tissues with altered mechanical stiffness, such as lung nodules. The quantitative data provided by the palpation device can be interpreted along with the results of other pre- and intra-operative techniques to give surgeons clearer insights into the location and margins of the nodules.

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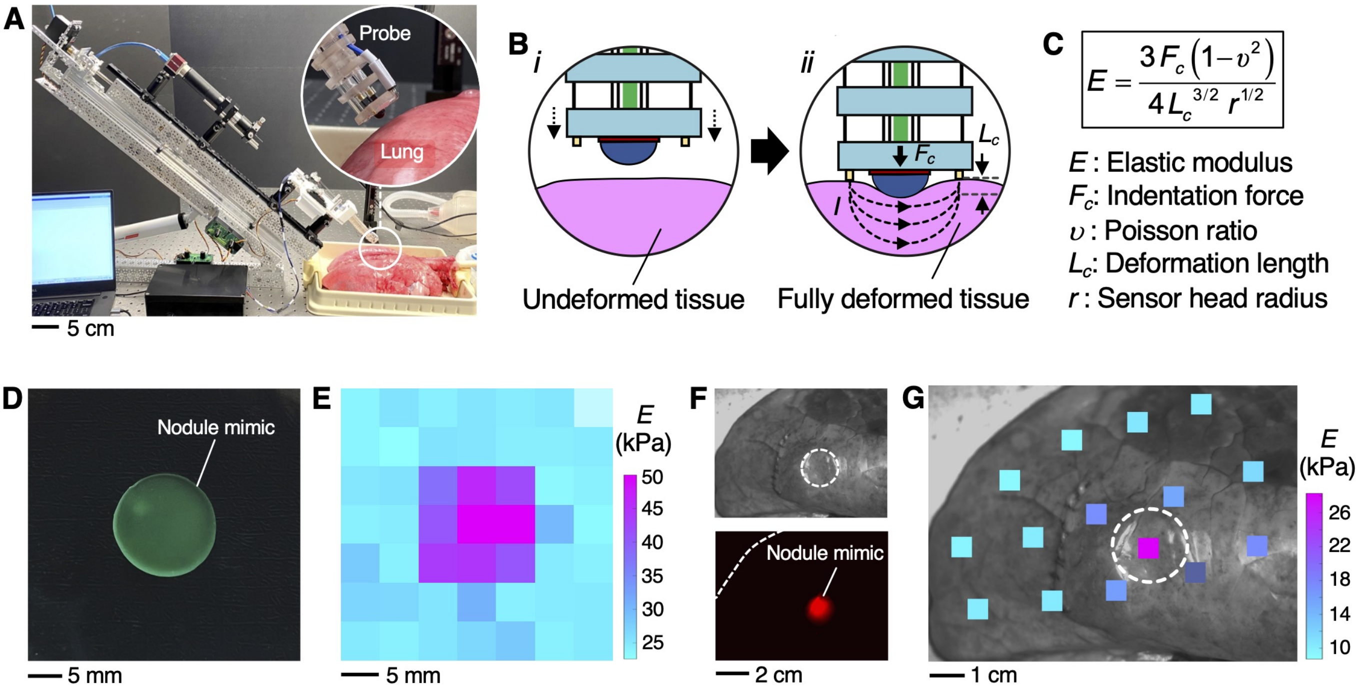

Fig. 1. Robotic tissue palpation device for intra-operative detection of lung nodules. (A) Photograph of the device and the measurement probe. **(B)** Schematic showing *i*) undeformed tissue and (*ii*) and fully deformed tissue (L_c: deformation length) under applied force (F_c). To determine the stiffness of tissue, the probe was directed downward perpendicular to the tissue surface (*i*). A force was then applied against the tissue surface via the probe to compress the tissue. The predefined magnitude of tissue deformation was confirmed when the electrical signal was detected across the contact electrodes (*ii*). Then, the elastic modulus (E) of the tissue was calculated by correlating the magnitude of the F_c and L_c. **(C)** Theoretical model for calculating the E **(D)** An ICG-labelled cylindrical-shaped silicone was embedded at the center of a gelatin block (concentration: 10%). **(E)** Two-dimensional (2D) stiffness map obtained following the measurement. **(F)** Bright-field and fluorescent images of the lung lobe with nodule mimic **(G)** Stiffness map of the lung cancer model. Dotted circle: nodule mimic.