Appendix 1

Subjects

The inclusion criteria were as follows: (I) age ≥18 years; (II) no acute respiratory infection or other severe pulmonary distortions such as interstitial lung diseases that could affect the quantitative CT measurement; (III) no previous thoracic operation; and (IV) the interval between CT examinations and spirometry within 2 weeks. The exclusion criteria were as follows: (I) poor cooperation with voice guidance during dynamic-ventilation CT; (II) incomplete spirometry measurement items; and (III) poor image quality that could not meet strain analysis.

CT scanning

CT scan parameters for chest CT were as follows: tube currents = automatic exposure control (AEC); tube voltage =120 kVp; scanning method = helical scanning; rotation time =0.35 s; beam pitch =0.828; imaging FOV =320 mm; collimation =0.5 mm ×80 rows; slice thickness =1 mm; reconstruction kernel = FC17 (for mediastinum); iterative reconstruction = adaptive iterative dose reduction using three-dimensional processing (AIDR3D; mild setting); slice thickness/interval =0.5 mm/0.5 mm.

Dynamic-ventilation CT was performed using dynamic volume scan mode (Z_{max} =16 cm) without bed movement. Two volumes of dynamic-ventilation CT with 1 cm overlap were set to cover the entire thorax. Scanning and reconstruction parameters for dynamic-ventilation CT were as follows: tube current =60 mA; tube voltage =80 kV; rotation time =0.35 s; total scanning time =8.4 s; imaging FOV =320 mm; collimation =0.5 mm; slice thickness =1 mm; reconstruction kernel = FC15 (for mediastinum); reconstruction interval =0.2 s/frame (total 41 frames); iterative reconstruction = AIDR3D (mild setting); slice thickness/interval =0.5 mm/0.5 mm.

Radiation dose assessment

Radiation exposure was calculated using dose-length product (DLP), which was based on CT dose index volumes (CTDIvol). The effective dose (ED) was calculated by multiplying DLP values by a conversion factor of k=0.014 $mSv \cdot mGy^{-1} \cdot cm^{-1}$. For conventional low-dose chest CT, the average DLP was 144.64 mGy·cm and average ED 2.02 mSv. For dynamic-ventilation CT, the average DLP was 521.6 mGy·cm and average ED 7.30 mSv.

Strain analysis progress

Strain analysis was performed on dynamic-ventilation CT using a CFD analysis software (MicroVec V3.6.2, MicroVec Pte Ltd.) as follows:

(I) Image matching and fusion. Using the motion coherence algorithm, the upper and lower volume data were matched and joined together. The overlapped cross sections in the dataset were deleted (*Figure S1*).

(II) Data abstraction. Script codes are used to extract all-frame data of different slices, respectively. The image format is converted from DICOM to Tiff.bmp, and the frequency of data acquisition is 10 Hz.

(III) The displacement field calculation. All-frame data of the same slice was imported into MicroVec software, and the irrelevant areas that were not included in the calculation were concealed by the "Mask" function. The cross-correlation algorithm was used to calculate the cross-correlation of lung image data and derive the maximum displacement time of those data.

(IV) The strain-related parameters calculation using the Tecplot macro-command. The values of strain-related parameters (PS_{max}, PS_{mean}, and $Speed_{max}$) were calculated and normalized using the following formula. PS_{max} and PS_{mean} referred to the maximum and average strain in the pixel displacement field (velocity field) based on pixel displacement, respectively. And $Speed_{max}$ was defined as the maximum displacement of pixel in the same velocity field.

$$PS_{max} = \frac{(Exx + Eyy)}{2} + \sqrt{\left(\frac{Exy + Eyx}{2}\right)^2 + \left(\frac{Exx + Eyy}{2}\right)^2} \quad [1]$$

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where E_{xx} is transverse strain, E_{yy} is longitudinal strain, and E_{xy} and E_{yx} are shearing strains.

(V) The final parameter diagram generation. The pseudo-color fusion image was generated by superimposing the values of different strain-related parameters on the original CT image.

The working mechanism of respiratory monitoring device

A mask was placed over the patient's mouth, along with a nose clip, to monitor respiratory flow. A signal converter translated the respiratory flow into an electronic signal, which was displayed as a sine wave on a screen (*Figure S2*). This allowed both the patient and the radiologist to observe real-time respiratory curve changes during the examination. After the upper volume scan was completed, the corresponding breath-hold curve (ren curve) remained on the screen. Patients could then adjust their breathing rate and amplitude using this curve as a visual reference during the second volume scan (yellow curve). Due to the limited Z-axis coverage of the CT scanner ($Z\text{-axis}_{max}$ =16 cm), two scan volumes were acquired to cover the entire lung during the dynamic-ventilation CT examination. The respiratory monitoring device guided patients to maintain consistent breathing patterns across both scan volumes.

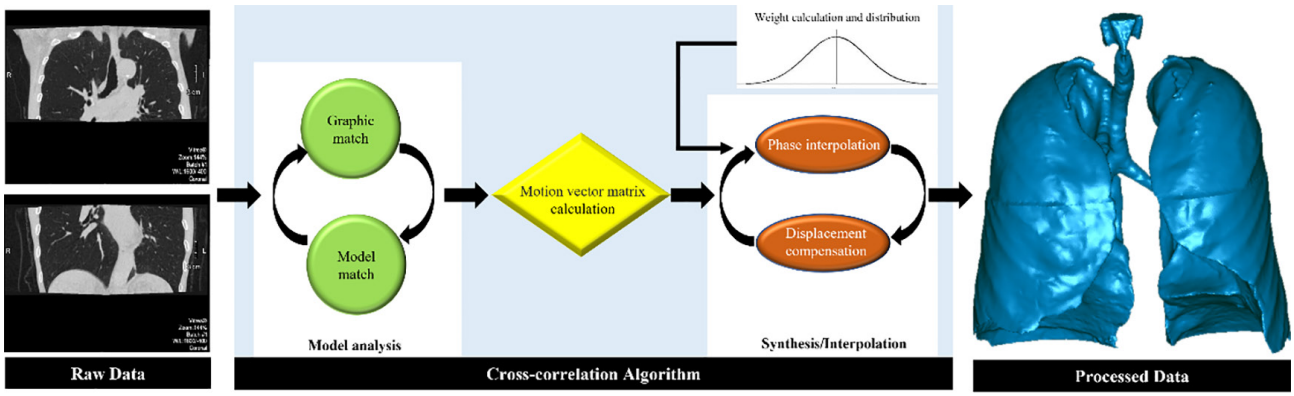

Figure S1 Data pre-processing: image matching and fusion.

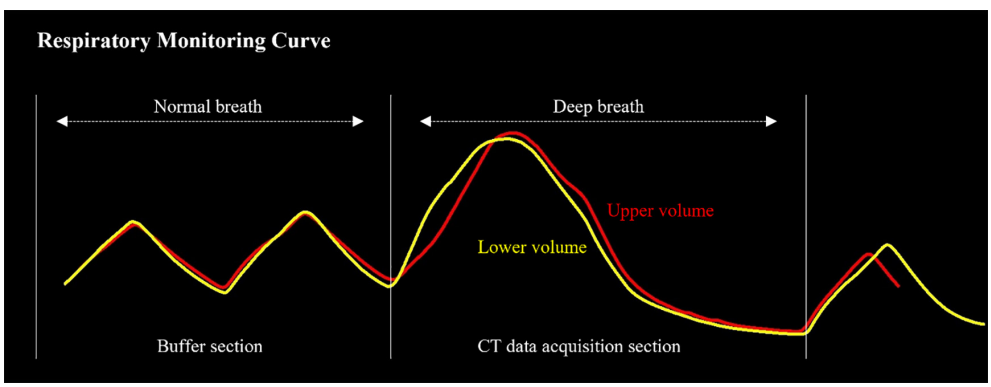

Figure S2 Respiratory monitoring curve. CT, computed tomography.

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Table S1 Percentage changes in CT quantitative parameters across GOLD stages in COPD patients

CT parameters	GOLD I (reference)	GOLD II (change from GOLD I), %	GOLD III–IV (change from GOLD I), %
Dynamic CT			
The whole expiration phase			
$PS_{max\text{-}all}$	203.78	−54.63	−74.69
$PS_{mean\text{-}all}$	26.81	−36.67	−104.77
$Speed_{max\text{-}all}$ (pixel/0.1 s)	31.06	−60.50	−69.22
The first 2-s of expiration phase			
PS_{max2s}	126.48	−41.23	−72.72
PS_{mean2s}	20.43	−32.75	−106.61
$Speed_{max2s}$ (pixel/0.1 s)	14.10	−61.13	−63.69
Static CT			
LD index (%)	5.60	71.43	556.25
TLV (L)	4.74	11.18	21.31

LD index is defined as the percent low attenuation (<−950 HU) volume of the whole lung. COPD, chronic obstructive pulmonary disease; CT, computed tomography; GOLD, Global Initiative for Chronic Obstructive Lung Disease; HU, Hounsfield units; LD, low-density; $PS_{max\text{-}all}$, maximum principal strain in the whole expiratory phase; PS_{max2s}, maximum principal strain in the first 2-s expiratory phase; $PS_{mean\text{-}all}$, mean principal strain in the whole expiratory phase; PS_{mean2s}, mean principal strain in the first 2-s expiratory phase; $Speed_{max\text{-}all}$, maximum displacement speed in the whole expiratory phase; $Speed_{max2s}$, maximum displacement speed in the first 2-s expiratory phase; TLV, total lung volume.

Table S2 Correlations between CT-derived parameters and spirometric indices

Correlation coefficients (ρ)	Spirometry							
	FVC	FEV_1	FEV_1/FVC	PEF	MMEF75%	MMEF50%	MMEF25%	MMEF25–75%
Dynamic-ventilation CT								
$PS_{max\text{-}all}$	0.239 (P=0.063)	0.367 (P=0.004)	0.386 (P=0.002)	0.394 (P=0.002)	0.439 (P<0.001)	0.444 (P<0.001)	0.392 (P=0.002)	0.449 (P<0.001)
$PS_{mean\text{-}all}$	0.325 (P=0.011)	0.380 (P=0.003)	0.428 (P=0.001)	0.357 (P=0.005)	0.418 (P=0.001)	0.412 (P=0.001)	0.484 (P<0.001)	0.442 (P<0.001)
$Speed_{max\text{-}all}$	0.338 (P=0.008)	0.481 (P<0.001)	0.436 (P<0.001)	0.283 (P=0.027)	0.416 (P=0.001)	0.520 (P<0.001)	0.404 (P=0.001)	0.491 (P<0.001)
PS_{max2s}	0.220 (P=0.089)	0.331 (P=0.009)	0.340 (P=0.007)	0.357 (P=0.005)	0.366 (P=0.004)	0.341 (P=0.007)	0.300 (P=0.019)	0.343 (P=0.007)
PS_{mean2s}	0.185 (P=0.154)	0.244 (P=0.058)	0.352 (P=0.005)	0.271 (P=0.035)	0.301 (P=0.018)	0.294 (P=0.021)	0.357 (P=0.005)	0.321 (P=0.012)
$Speed_{max2s}$	0.226 (P=0.080)	0.367 (P=0.004)	0.444 (P<0.001)	0.230 (P=0.074)	0.295 (P=0.021)	0.399 (P=0.001)	0.319 (P=0.012)	0.381 (P=0.002)
Static CT								
LD index	−0.229 (P=0.076)	−0.401 (P=0.001)	−0.426 (P=0.001)	−0.259 (P=0.044)	−0.417 (P=0.001)	−0.477 (P<0.001)	−0.532 (P<0.001)	−0.483 (P<0.001)

All strain-related parameters have been adjusted by corresponding volume changes. LD index is defined as the percent low attenuation (<−950 HU) volume of the whole lung. CT, computed tomography; FEV_1, forced expiratory volume in 1 s; FVC, forced vital capacity; HU, Hounsfield units; LD, low-density; MMEF, maximum mid-expiratory flow; PEF, peak expiratory flow; $PS_{max\text{-}all}$, maximum principal strain in the whole expiratory phase; PS_{max2s}, maximum principal strain in the first 2-s expiratory phase; $PS_{mean\text{-}all}$, mean principal strain in the whole expiratory phase; PS_{mean2s}, mean principal strain in the first 2-s expiratory phase; $Speed_{max\text{-}all}$, maximum displacement speed in the whole expiratory phase; $Speed_{max2s}$, maximum displacement speed in the first 2-s expiratory phase.

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