Measurement Techniques

Non-invasive quantification of diaphragm kinetics using m-mode sonography

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Purpose: The standard conditions of spirometry (i.e., wearing a noseclip and breathing through a mouthpiece and a pneumotachograph) are likely to alter the ventilatory pattern. We used "time-motion" mode (M-mode) sonography to assess the changes in diaphragm kinetics induced by spirometry during quiet breathing.

Methods: An M-mode sonographic study of the right diaphragm was performed before and during standard spirometry in eight patients without respiratory disease (age 34 to 68 yr).

Results: During spirometry, the diaphragm inspiratory amplitude (DIA) increased from 1.34 ± 0.18 cm to 1.80 ± 0.18 cm ($P = 0.007$), whereas the diaphragmatic inspiratory time (T_i diaph) increased from 1.27 ± 0.15 to 1.53 ± 0.23 sec, ($P = 0.015$), without change in diaphragmatic total time interval (Ttot diaph). Therefore, the diaphragm duty cycle (T_i diaph /Ttot diaph) increased from 38% ± 1% to 44% ± 4% ($P = 0.023$). The diaphragm inspiratory (DIV) and expiratory (DEV) motion velocity increased ($P = 0.007$).

Conclusion: M-mode sonography enabled us to demonstrate that the wearing of a nose clip and breathing through a mouthpiece and a pneumotachograph induce measurable changes in diaphragm kinetics.

Objectif : Les conditions de la spirométrie standard (c.-à-d. le port du pince-nez et la respiration à travers un embout buccal et un pneumotacographe) sont susceptibles d'altérer la morphologie de la ventilation. Nous avons utilisé le mode «temps-amplitude» (mode M) de la sonographie pour évaluer les changements de la cinétique diaphragmatique provoqués par la spirométrie pendant la respiration de repos.

Résultats : Pendant la spirométrie, l'amplitude inspiratoire diaphragmatique augmentait de 1,34 ± 0,18 à 1,80 ± 0,18 cm ($P = 0,007$), alors que le temps diaphragmatique inspiratoire (T_i diaph) augmentait de 1,27 ± 0,15 à 1,53 ± 0,23 sec ($P = 0,015$), sans changement du temps diaphragmatique total (Ttot diaph). Par conséquent, le temps de l'activité diaphragmatique (T_i diaph/Ttot diaph) augmentait de 38 ± 1 % à 44 ± 4% ($P=0,023$). La vélocité de l'amplitude inspiratoire et expiratoire augmentait ($P = 0,007$).

Conclusion : La sonographie en mode M nous a permis de démontrer que le port du pince-nez et la respiration à travers un embout buccal et un pneumotacographe provoquent des changements tangibles de la cinétique diaphragmatique.

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DIAPHRAGMATIC movements play an essential role in the respiratory process, but the observation of diaphragm kinetics is a challenge because most available techniques are more or less directly invasive (electromyography and pressure measurements) or employ ionising radiations (X-ray fluoroscopy). Although several authors have reported the use of ultrasound for the evaluation of diaphragmatic displacement,[1-9] most have used real-time B-mode sonography (by rapidly sweeping the ultrasound beam across a scan plane, a large number of bi-dimensional images representing anatomical sections can be produced and displayed every second, allowing the so-called real-time observation of moving structures.). In 1975, Haber *et al.*[10] used sonography in patients with pleural effusion or various abdominal pathologies, and, incidentally, pointed out the potential usefulness of M-mode sonography without, however, stating any results.

M-mode sonography traces the position of structures along the ultrasound beam *vs* time. Although this technique allows measurement of the kinetics of any moving structure, it has been used so far mostly for cardiology. Recently, Wait *et al.*[11] studied diaphragmatic function by M-mode sonographic measurement of diaphragm thickness, and Heyman *et al.*[12] used M-mode sonography to record diaphragmatic excursion in preterm neonates.

A mouthpiece (MP) connected to a pneumotachograph and a noseclip (NC) are standard for the assessment of respiratory function. The effects of these devices on ventilatory patterns have been demonstrated[13] and studied by inductive plethysmography.[14-15] Nevertheless, the role of the diaphragm in the observed changes could not be directly assessed by this technique. Therefore, we designed a study using M-mode sonography for the direct measurement of diaphragm displacement in humans breathing freely then wearing the noseclip and breathing through the mouthpiece and pneumotachograph.

Material and methods

Population.

The subjects were patients referred to the laboratory for systematic preoperative evaluation of respiratory function and for abdominal sonographic examination before elective cholecystectomy. They were fully informed of the study purpose, methods and constraints, these last being very limited. Written consent was obtained from all patients.

Patients were excluded if history, physical examination, or the usual preoperative tests (ECG, standard chest X-ray) revealed any past or present disease other than biliary pathology requiring cholecystectomy. Special care was taken in the search for signs or symptoms of respiratory or neuromuscular pathology. Eight patients (six women, two men), aged 34–68 yr, participated in the study (Table I).

TABLE I Population

Patient	*Sex*	*Age (yr)*	*Weight (kg)*	*Height (m)*
1	M	55	70	1.7
2	M	63	82	1.72
3	F	37	62	1.6
4	F	68	62	1.55
5	F	46	77	1.65
6	F	58	62	1.54
7	F	34	50	1.57
8	F	44	58	1.59

Sonography

A real-time, sector scanning sonographic system with a 3.5 MHz curved array probe (Aloka 650®, Aloka, Japan) was used. B-mode was used to obtain the bi-dimensional cross section, to find the best approach and to select the exploration line; M-mode was then used to display the motion of the anatomical structures found along this line (Figure 1*A*). The probe was placed on the anterior axillary line, in the subcostal area, and directed medially, cephalad, and dorsally, so that the ultrasound beam reached nearly perpendicularly the posterior part of the vault of the right diaphragm (Figure 1*A*), 5 cm lateral to the inferior vena cava foramen. Thus, the inspiratory and expiratory cranio-caudal displacement of the diaphragm respectively shortened and lengthened the probe-diaphragm distance. Consequently, the bright line formed by echoes originating from the diaphragm successively moved upward and downward on the M-mode graph. The M-mode sonogram was displayed on the video screen with a horizontal sweep speed of 1 $cm \cdot sec^{-1}$, and was continuously recorded on videotape.

Spirometry

Air flow was measured using a Fleisch pneumotachograph, and ventilatory volumes were measured by time-integration of the flow signal through a linear demodulator and amplifier (model MRC 4411, LEIM®, Aix en Provence, France). The air flow signal was displayed on the screen of the sonographic device, together with M-mode graphs. Air flow and volume signals were also recorded for subsequent measurement on a chart recorder TA 550® (GOULD) with a 1 $cm \cdot sec^{-1}$ paper streaming speed. A one-litre syringe was used before and after examination for calibration

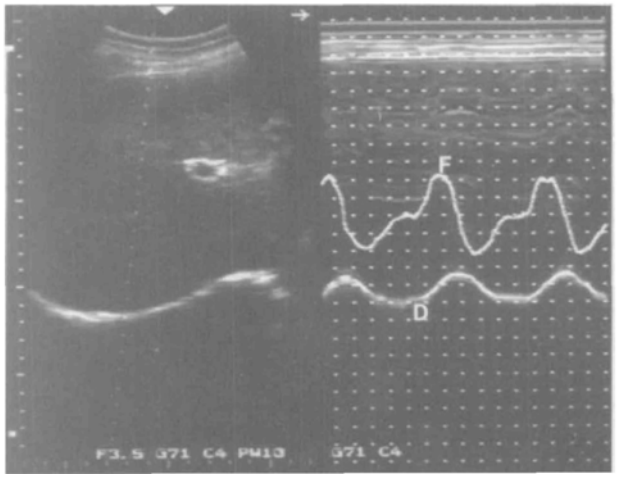

FIGURE 1 Diaphragm sonograms in a normal subject breathing through the mouth piece. A, B-mode sonogram (left) showing the diaphragm as a bright echoic line, and the M-mode marker as a dotted line; M-mode sonogram (right) showing the diaphragm motion tracing (D) with the superimposed air flow tracing (F).

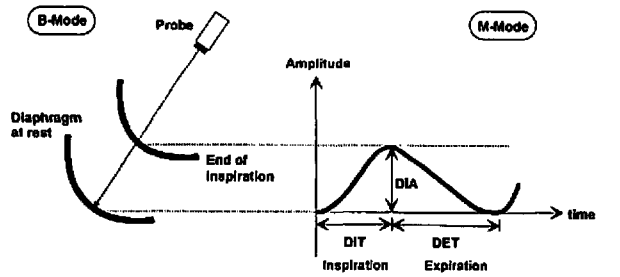

FIGURE 1B Schematic drawing showing the ultrasound beam incidence on the diaphragm at rest and at the end of inspiration (left), and the resulting M-mode tracing with measurement of DIA, T_I diaph, and T_E diaph.

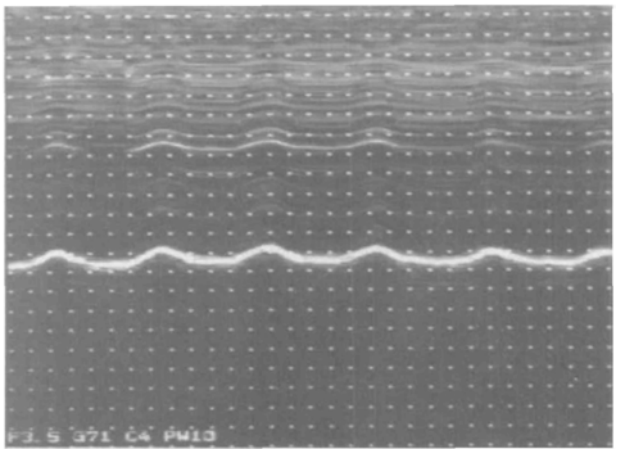

FIGURE 2 M-mode tracings and air flow signal during quiet breathing in the same patient. A, before spirometry.

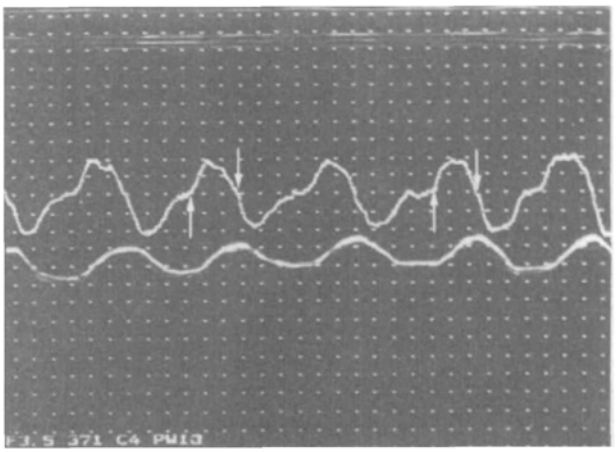

FIGURE 2B During spirometry. Up arrow, beginning of inspiration; down arrow, beginning of expiration.

of volume measurement. Results were expressed in BTPS (body temperature pressure saturated). The mouthpiece was of the standard diameter.

Protocol

Each patient fasted for four hours and had an empty stomach and urinary bladder, as verified by sonographic examination. The patient lay in the semi-supine position (30) and rested for at least 15 min before the examination.

The sonographic examination was first performed in B-mode for visualisation of the diaphragm and major abdominal organs, and for the detection of any morphological abnormality. Diaphragm movements were recorded in M-mode during quiet ventilation (Figure 2*A*). Then, the mouthpiece connected to the pneumotachograph and noseclip were installed, and, in the same semi-supine position, the patient was asked to breathe quietly for 10 min before standard spirometry was performed, while diaphragm movements were continuously recorded in M-mode (Figure 2*B*).

Parameters

Several parameters were measured during inspiration and expiration on the M-mode graph (Figure 1*B*) using electronic calipers for each respiratory cycle, and were then averaged over 10 cycles. During inspiration,

TABLE II Sonographically measured diaphragmatic variables before and during spirometry. Mean ± SD.

Variable	*Before Spirometry*	*During Spirometry*	*P*
Diaphragm Inspiratory Time T_I diaph (sec)	1.27 ± 0.15	1.53 ± 0.23	0.01
Diaphragm Expiratory Time T_E diaph (sec)	2.06 ± 0.17	1.92 ± 0.30	0.77
Diaphragm Total Time T_{tot} diaph (sec)	3.33 ± 0.32	3.45 ± 0.41	0.65
Diaphragm Inspiratory Ratio T_I diaph/T_{tot} diaph (%)	38 ± 1	44 ± 4	0.02
Diaphragm Resting Time DRT (sec)	0.47 ± 0.14	0.22 ± 0.12	0.007
Diaphragm inspiratory Amplitude DIA (cm)	1.34 ± 0.18	1.80 ± 0.18	0.007
Diaphragm Ispiratory velocity DIV (cm·sec^{-1})	1.11 ± 0.11	1.29 ± 0.13	0.007
Diaphragm Expiratory velocity DEv (cm·sec^{-1})	0.86 ± 0.14	1.10 ± 0.18	0.007
Diaphragm Motion Time DMT (sec)	2.86 ± 0.32	3.23 ± 0.37	0.05

TABLE III Breathing variables measured by spirometry.

	Mean (SD)
Inspiratory Time (T_I, sec)	1.40 ± 0.18
Expiratory Time (T_E, sec)	1.95 ± 0.27
Total Time (T_{tot}, sec)	3.35 ± 0.40
Inspiratory Duty cycle (T_I/T_{tot},%)	41 ± 3
Tidal Volume (V_T, l)	0.502 ± 0.1
Mean Inspiratory Flow (V^T/T_I, l·sec^{-1})	0.36 ± 0.08

the first caliper was placed at the foot of the inspiration slope on the diaphragm echoic line; the second caliper was placed at the apex of this slope. The distance shift on the Y-axis, i.e., the diaphragm inspiratory amplitude (DIA, in cm), was divided by the time interval on the X-axis (diaphragm inspiratory time, T_I diaph, in sec), giving the diaphragm inspiratory motion mean velocity (DIV, in cm·sec^{-1}).

During expiration, the same measurements were perfomed between the beginning and the end of the expiratory slope, giving the diaphragm expiratory amplitude (DEA, in cm) with an absolute value identical to that of the DIA, the time interval (diaphragm expiratory time, T_E diaph, in sec), and the diaphragm expiratory velocity (DEV in cm·sec^{-1}).

The breathing period was measured as the total time interval (T_{tot} diaph, in sec) from the foot of one inspiration slope to the foot of the next. The inspiratory ratio was calculated as T_I diaph./ T_{tot} diaph.

The diaphragm motion time (DMT, in sec) was measured as the time interval from the foot of an inspiration slope to the end of the following expiration slope. The diaphragm resting time (DRT, sec), defined as the motionless period from the end of the expiration slope to the foot of the following inspiration slope, was calculated as T_{tot} diaph - DMT.

The following parameters were measured on spirometric graphs: tidal volume (V_T, l), inspiratory time (T_I, sec), expiratory time (T_E, sec), mean inspiratory flow (V_T/T_I, l·sec^{-1}), total time (T_{tot}, sec), and inspiratory duty cycle (T_I/ T_{tot}, in %).

Statistics

The statistical calculations were performed on a Microvax II computer with the help of the SAS v 6.0 software (SAS Institute Inc). Sonographic and spirometric data were compared using the Wilcoxon signed-rank test. Correlations between parameters were evaluated by the Spearman coefficient and its comparison with 0. Results are given hereafter as mean ± 1 SD.

Results

The examination was successfully completed in all eight patients (Tables II and III). The DRT before spirometry ranged from 0.21 to 0.69 sec, and decreased by 52.8% ± 21.7% during spirometry (P = 0.007), whereas there was an increase in T_I diaph (P = 0.01) and DIA (P = 0.007), but no change in T_{tot} diaph. Therefore, T_I diaph/T_{tot} diaph increased from 38 ± 1% to 44 ± 4% (P = 0.02) (Table II). There was no difference between time variables measured by sonography (Table II) and by spirometry (Table III). There was a intra-individual, but not interindividual, correlation between DIA during quiet breathing and V_T (r = 0.98; P = 0.0001).

There was no time delay between air flow and diaphragm motion at the beginning of inspiration and expiration during quiet breathing (Figure 2).

Discussion

This study showed that during spirometry there was a change in the direct measurements of diaphragmatic ventilatory pattern. Our results demonstrate that spirometry, in itself, causes alteration in diaphragmatic kinetics, increasing the duration of the diaphragm displacement time at the expense of resting time,

which was reduced by about 52%. Moreover, the DIA increased during spirometry, with a subsequent increase in DIV, DEV and T_I diaph/T_{tot} diaph without change in T_{tot} diaph. We have found no data in the literature about modifications in diaphragm amplitude induced by techniques and during spirometry nor about the speed of diaphragm motion.

Using this method, we were able to measure the amplitude, duration, and speed of diaphragm movements during inspiration and expiration, as well as the diaphragm resting period in all eight patients. Our results concerning the amplitude of diaphragm movement (1.34 cm mean DIA before spirometry) are in agreement with those found by Whitelaw[16] (1.5 cm) using CT-scanning. Houston *et al.*[17] studied diaphragmatic excursions by ultrasound. They demonstrated the reproducibility of this technique

Before spirometry, we observed three successive phases of diaphragm displacement: diaphragm descent during inspiration (T_I diaph, mean duration 1.27 sec), raising (T_E diaph, mean duration 2.06 sec), and resting time (DRT, mean duration 0.47 sec). Although the descending phase is obviously related to the diaphragm muscle contraction, the simultaneous recording of electromyography activity would have enabled us to assess more accurately the physiological meaning of these phases. Kobylarz and Daubenspeck[18] observed that the diaphragm electrical activity remains at its baseline level for some time at the end of expiration. This inactivity phase probably corresponds to the DRT we measured by sonography.

Employment of a MP and NC has repeatedly been shown to increase V_T, but its effect on respiratory frequency and its subsets is controversial. The mechanisms accounting for this alteration in breathing pattern are poorly understood and may include stimulation of nasal sensory receptors or alteration in the route of breathing. The use of MP and NC, alters the majority of the volume and time indexes of breathing pattern, essentially with increases in V_T and T_I and a decrease in respiratory frequency.[19–20] Rodenstein *et al.*[14] observed a significant increase in V_T (from 0.5 to 0.7 l) during spirometry when the NC was installed. These authors demonstrated that the simple use of the MP (disconnected from the spirometer) increased V_T (from 0.46 to 0.57 l), without change in T_{tot} and in minute ventilation, the T_I/T_{tot} increasing from 37 to 41%. They concluded that the changes in breathing pattern observed when performing spirometry were mainly due to the air flow being forced through the buccal instead of nasal airways. Ramonatxo *et al.*[21] found that the inspiratory resistive load induced a prolongation of T_I with a decrease in V_T/T_I and an increase of V_T and T_I/T_{tot}. The meaning of these changes during spirometry could be related to the slight additional serial resistance created by the MP and the pneumotachograph. Indeed, Weissman *et al.*[13] demonstrated that these changes were eliminated when the MP diameter was reduced from the original 17 to only 9 mm. Physiological mechanisms are also likely to be involved, as a response to the unusual condition created by the use of a MP and NC. Irritation and stimulation of the nasal mucosa depresses the respiratory frequency in both man and lower animals;[22] it thus seems likely that the fall in respiratory frequency produced by the respiratory apparatus was related to the irritating effects of the noseclip and mouthpiece on the nasal and oral mucosa. If so, the increase in V_T can be considered secondary and serves to maintain adequate ventilation.[20] As a matter of fact, the observed changes under spirometry decreased progressively with time, without returning to basal values. We found no correlation between the V_T and DIA ($P = 0.056$). Besides the small number of patients, the reason may be that thoracic and abdominal expansion is relatively independent from diaphragm excursion.[23]

M-mode sonography allows continuous recording in real time of diaphragm displacements, with measurement of their amplitude, duration, and velocity. Examination of the left hemidiaphragm remains difficult because of the limited acoustic window offered by the spleen. M-mode sonography proved to be a simple, well tolerated, reproducible method of assessing hemidiaphragmatic movement. Its advantages over fluoroscopy are lack of risk from ionising radiation, portability, and direct quantitative information on the greatest amplitude and velocity of hemidiaphragmatic movement. This method can be easily coupled with other techniques, such as pressure and air flow measurement, for phase relationship assessment and for comparative studies.[24–25] We obtained simultaneous display, on the sonographic system display, of M-mode and air flow graphs. M-mode sonography offers high spatial and time resolution, thus allowing accurate measurement of absolute distance of diaphragm displacement.

Non invasive quantification of diaphragm kinetics may be useful for the follow-up of diaphragmatic paralysis or fatigue, as well as for the evaluation of drug induced changes in contractility. We also used this technique for the study of diaphragm kinetics after abdominal surgery, and to assess the efficacy of pneumatic belt ventilatory assistance in patients with Duchenne muscular dystrophy.

In conclusion, our work demonstrated non-invasively that wearing a NC and breathing through a pneumotachograph alters diaphragm kinetics, by

increasing the diaphragm inspiratory excursion amplitude, duration, and speed. The M-mode sonography technique should prove to be a very useful complement to spirometry in many circumstances, for the analytic study of diaphragm kinetics in physiological as well as pathological conditions.

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Abbreviations

M-mode sonography, time-motion mode sonography; DIA, diaphragm inspiratory amplitude; T_I diaph, diaphragm inspiratory time; T_E diaph, diaphragm expiratory time; DIV, diaphragm inspiratory motion mean velocity; DEV, diaphragm expiratory motion mean velocity; T_{tot} diaph, total time of diaphragmatic cycle; T_I/T_{tot} diaph, the diaphragmatic inspiratory ratio; DMT, diaphragm motion time; DRT, diaphragm resting time.

V_T, tidal volume; T_I, inspiratory time; T_E, expiratory time; V_T/T_I, mean inspiratory flow; T_{tot}, total time; T_I/T_{tot}, inspiratory duty cycle.