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Original Article

Modifications of Diaphragmatic Activity Induced by Midline Laparotomy and Changes in Abdominal Wall Compliance

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ABSTRACT

Introduction and Objective. Diaphragmatic activity varies with the initial length of the muscle. Our objective was to evaluate the influence of surgery and changes in abdominal wall compliance on diaphragmatic activity.
Methods. Both phrenic nerves in 7 mongrel dogs were stimulated electrically with single supramaximal pulses (twitch). The gastric (Pga) and transdiaphragmatic (Pdi) pressures generated and muscle shortening (sonomicrometry) were used to evaluate diaphragmatic activity, which was determined at baseline, after midline laparotomy, with an elastic abdominal bandage, and with a rigid circular cast. Abdominal pressure was then gradually increased in order to induce progressive lengthening of the diaphragm.
Results. After laparotomy, the pressures were somewhat lower (by 12%) than at baseline. The elastic bandage produced a slight increase in the pressure generated by the diaphragm (mean [SE] values: Pga, from 4.2 [0.3] cm H_2O to 6.3 [0.9] cm H_2O, $P<.01$; Pdi, from 12.1 [2.0] cm H_2O to 15.4 [1.8] cm H_2O, $P<.05$]), and these values increased even further with the rigid cast (Pga, to 12.6 [1.5] cm H_2O; Pdi, to 20.2 [2.3] cm H_2O; $P<.01$ for both comparisons); this occurred despite smaller degrees of muscle shortening: by 57% [5%] of the initial length at functional residual capacity at baseline, by 49% [5%] with the bandage ($P<.05$), and by 39% [6%] with the cast ($P<.01$). With progressive lengthening of the muscle, its contractile efficacy increased up to a certain point (105% of the length at functional residual capacity), after which it began to decline.
Conclusions. Abdominal wall compliance plays an important role in the diaphragmatic response to stimulation. This appears to be due mainly to changes in its length at rest.

Modificaciones en la actividad del diafragma inducidas por laparotomía media y cambios en la rigidez de la pared abdominal

Palabras clave:
Diafragma
Cirugía abdominal
Prótesis abdominal
Longitud muscular

RESUMEN

Introducción y objetivos. La actividad del diafragma puede verse modificada por su longitud inicial. Nuestro objetivo ha sido evaluar la influencia de la cirugía y los cambios en la rigidez de la pared abdominal sobre la actividad del músculo.
Método. En 7 perros mestizos se estimularon eléctricamente ambos nervios frénicos con pulsos únicos supramáximos (*twitch*). Para evaluar la actividad del diafragma se determinaron las presiones generadas –gástrica (Pga_{tw}) y transdiafragmática (Pdi_{tw})– y el acortamiento muscular (sonomicrometría). La respuesta diafragmática se obtuvo en situación basal, tras laparotomía media, con venda abdominal elástica y con

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prótesis rígida circular. A continuación se incrementó ligera y progresivamente la presión abdominal para conseguir el alargamiento sucesivo del diafragma.
Resultados. Tras la laparotomía, las presiones fueron algo inferiores a las basales (12%). La banda elástica provocó un leve aumento de la presión generada por el diafragma (valores medios ± error estándar. Pga_{tw}: 4,2 ± 0,3 a 6,3 ± 0,9 cmH_2O, p < 0,01; Pdi_{tw}: 12,1 ± 2,0 a 15,4 ± 1,8 cmH_2O, p < 0,05), que se incrementó aún más con la prótesis rígida (Pga_{tw}: 12,6 ± 1,5 cmH_2O; Pdi_{tw}: 20,2 ± 2,3 cmH_2O; p < 0,01 para ambas), a pesar de valores de acortamiento inferiores –un 57 ± 5% de la longitud inicial a capacidad funcional residual en situación basal, un 49 ± 5% con banda (p < 0,05) y un 39 ± 6% con prótesis (p < 0,01)–. Al alargar progresivamente el músculo, su efectividad contráctil aumentó hasta un punto (un 105% de la longitud a capacidad funcional residual) a partir del cual comenzó a declinar.
Conclusión. La rigidez de la pared abdominal desempeña un papel importante en la respuesta del diafragma a la estimulación. Esto parece deberse fundamentalmente a cambios en su longitud de reposo.

Introduction

The diaphragm is the principal inspiratory muscle in healthy individuals. Its contraction and descent, combined with the elastic retraction of the lung, produce an increase in the negative pleural pressure; transmission of this negative pressure to the alveolar space causes air to enter the lungs. Diaphragmatic contraction is affected by a number of factors, one of the important ones being the initial (resting) length of the muscle, which can vary not only with changes within the chest, but also with alterations in the abdomen. In the chest, hyperinflation of the lungs is known to alter the geometry of the diaphragm, flattening and shortening it, to the detriment of diaphragmatic function.[1,2] However, the effect of certain changes in the stiffness of the abdominal wall is less well known. These changes can alter the pressure within the abdominal cavity, potentially lengthening or shortening the diaphragm. Examples of clinical situations that affect the stiffness of the wall are upper abdominal surgery and the use of prostheses for abdominal wall reconstruction or orthopedic corsets.

Twitch stimulation of the diaphragm is a widely accepted method for evaluating diaphragmatic function in both clinical and experimental settings.[2-6] This technique uses electric or magnetic stimulation of both phrenic nerves simultaneously and its advantages over voluntary maximal maneuvers, which are more widely used in clinical practice and which may be static (eg, Müller) or dynamic (eg, sniff), include the possibility for use in unconscious or noncollaborative individuals and in experimental animals. In addition, there is the certainty that the whole diaphragm is recruited, and the pressure generated therefore reflects the maximum tension or strength of contraction of the muscle. The disadvantages of stimulation include the cost of the specialized equipment and the need for training in applying the technique and interpreting the results correctly.

The objective of this study was to measure the change in the contractile response of the diaphragm caused by variations in abdominal wall stiffness and in the initial length of the diaphragm. The study was performed in vivo in a previously validated canine model.[7-9]

Method

Animal Model

The protocol was approved by the ethics committee for animal research of Hôpital de Notre Dame, Montréal, and efforts were made at all times to minimize the suffering of the animals. Seven mongrel dogs weighing 20 to 25 kg were anesthetized with 25 mg/kg of intravenous sodium pentobarbital and an upper midline laparotomy was performed. During the operation, anesthesia was maintained with inhaled halothane. The animals were placed in the supine position and were ventilated mechanically (Mark-8 Respiratory, Bird Corporation, Palm Springs, California, USA) through an endotracheal tube. After closure of the laparotomy, inhaled anesthesia was withdrawn and the dogs breathed spontaneously through the endotracheal tube. During this phase of the study, anesthesia was maintained with doses of pentobarbital sufficient to block the corneal reflex and keep the mandible relaxed.[7-9] The dogs were kept warm throughout the procedure by the surgical lamps.

Procedures

Electrical stimulation. Bipolar electrodes were introduced into the jugular vein, with the tip close to each phrenic nerve (Figure 1A).[7] Stimulation was performed using single bilateral pulses of supramaximal intensity (approximately 8 V and 50 Hz, with a duration of 0.25 ms).[8] To determine this intensity, the stimulus to each nerve was progressively increased until a maximal response was achieved and the intensity was then increased a further 30%. The stimuli were always administered at the end of expiration, determined by the esophageal pressure curve, and with the airway occluded. At least 3 reproducible maneuvers were performed for each experimental condition described below.

Diaphragmatic response. Muscle shortening and the pressures generated were evaluated. The pressures were measured using balloon catheters placed in the esophagus and stomach (Figure 1A). The catheters were connected to pressure transducers (Validyne MP45-18, Northridge, California, USA) that were calibrated at the start of each study. The transdiaphragmatic pressure (Pdi) was calculated from the arithmetic difference between the gastric (Pga) and esophageal (Pes) pressures.[10] Muscle shortening was determined by sonomicrometry; the initial length at functional residual capacity ($_{i}$FRC) and the speed and intensity of contraction of each hemidiaphragm were measured on the costal part of the muscle. For this purpose, a pair of piezoelectric crystals were placed in parallel on the same muscle fibers, separated by 10 to 13 mm (Figure 1B), and connected to a sonomicrometer (Triton Technology Inc, San Diego, California, USA). The crystals were placed through the laparotomy, which was then closed by tissue planes. The length of the diaphragm at any given moment, its contractile shortening, and instrumentally induced stretching were expressed as percentages of the initial (resting) length of the muscle ($_{i}$FRC%). The contractile speed was expressed as the percentage distance covered (in relation to the resting length) per second ($_{i}$FRC%/s).

Data recording. Stimulation pulses, pressure signals, relative length of each hemidiaphragm, and blood pressure were recorded on an 8-channel analog polygraph (HP 7758 B, Hewlett-Packard, Palo Alto, California, USA) and were then digitized and analyzed (Anadat-Labdat software, Rht-Info, Montréal, Québec, Canada).

Abdominal binding with an elastic bandage or plaster cast. We studied the effect of abdominal binding with an elastic bandage or rigid (plaster) cast on the contractile response of the diaphragm. Both binding methods were applied from the xiphoid process to the iliac crests. A circular orifice that could be closed was made anteriorly

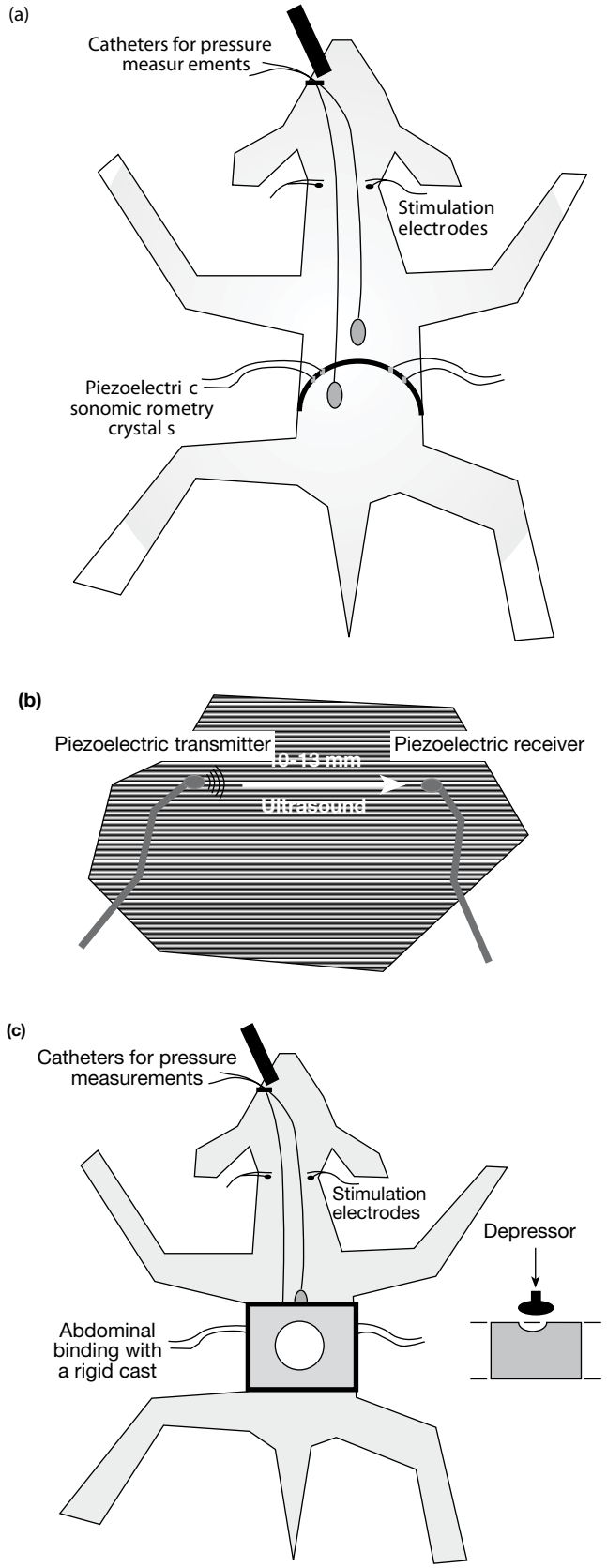

Figure 1. Diagram of the animal model
A, sites of the electrodes (intravascular path, tip close to the phrenic nerves), piezoelectric sonomicrometry crystals (both costal hemidiaphragms), and balloon catheters for measurement of gastric and esophageal pressures. B, details of the site on the muscle of the piezoelectric crystals; the distance between the crystals was measured at rest and during the contraction-relaxation cycles. C, position of the rigid abdominal cast, with the sealable orifice that permitted the application of additional pressure.

in the plaster cast, at the level of the mesogastrium (Figure 1C); through this orifice, the pressure could be slightly increased using a plunger operated manually by means of a lever system.

Protocol

We first measured the baseline pressures. The pressures and the characteristics of muscle contraction after stimulation were then determined during laparotomy and under the following experimental conditions: *a)* with the abdomen open, *b)* after closure of the laparotomy, *c)* after abdominal binding with the elastic bandage, and *d)* after abdominal binding with the plaster cast without additional pressure. Four increasing levels of abdominal pressure were then applied in order to gradually increase the length of the diaphragm prior to contraction. At the end of the study, euthanasia of the animals was performed by means of pentobarbital overdose.

Statistical Analysis

All measurements are expressed as mean (SD). Analysis of variance for repeated measures was used to compare the results under the different experimental conditions. Correlation analysis (Pearson correlation coefficient) and multiple regression were used when appropriate. Significance was established at a P value of .05.

Results

Effect of the Laparotomy

During laparotomy, after placement of the sonomicrometry crystals, stimulation of the diaphragm provoked shortening that hardly increased abdominal pressure (Figure 2A), with changes only being observed in Pes (Figure 2B). After closure of the laparotomy, Pga did increase, but somewhat less than the before surgery (12%; P<.05); there was a similar trend in Pdi (Table).

Effect of Abdominal Binding With the Elastic Bandage or Rigid Cast

Abdominal binding with the elastic bandage or rigid cast produced moderate lengthening (5% and 8%, respectively, over the $_{i}$FRC%). These increases in length showed an excellent correlation (r=.983; P<.001) and were similar for both hemidiaphragms. Subsequent stimulation produced higher pressures to those obtained with the abdomen open, despite a reduction in muscle shortening. The Table shows the mean values of the pressures, muscle shortening, and speed of contraction before and after abdominal binding with the elastic bandage and with the cast. In fact, both Pga and Pdi induced by stimulation showed major increases (50% and 27%, respectively, with the bandage, and 200% and 66% with the cast). In contrast, the degree of muscle shortening during contraction fell by 15% and 31%, respectively, and was more marked in the left hemidiaphragm (falling by 15% and 39% vs 14% and 24% on the right side). The speed of contraction changed slightly with the elastic bandage and with the cast, passing from 3.8 [0.2] $_{i}$FRC%/s just after closure of the laparotomy to 3.5 [0.2] $_{i}$FRC%/s with the elastic bandage and from 3.5 [0.2] $_{i}$FRC%/s to 3.0% [0.3%] $_{i}$FRC%/s with the cast. Figure 2 shows the relationships between length and Pga and Pes during the laparotomy, after closure of the abdomen, and after binding with the elastic bandage or plaster cast.

Effect of Muscle Length

Muscle length increased progressively with rising abdominal pressure. Efficacy of contraction reached a maximum at approximately 105% of $_{i}$FRC (Figure 3). At this length, small degrees of muscle shortening gave rise to large changes in pressure, but further

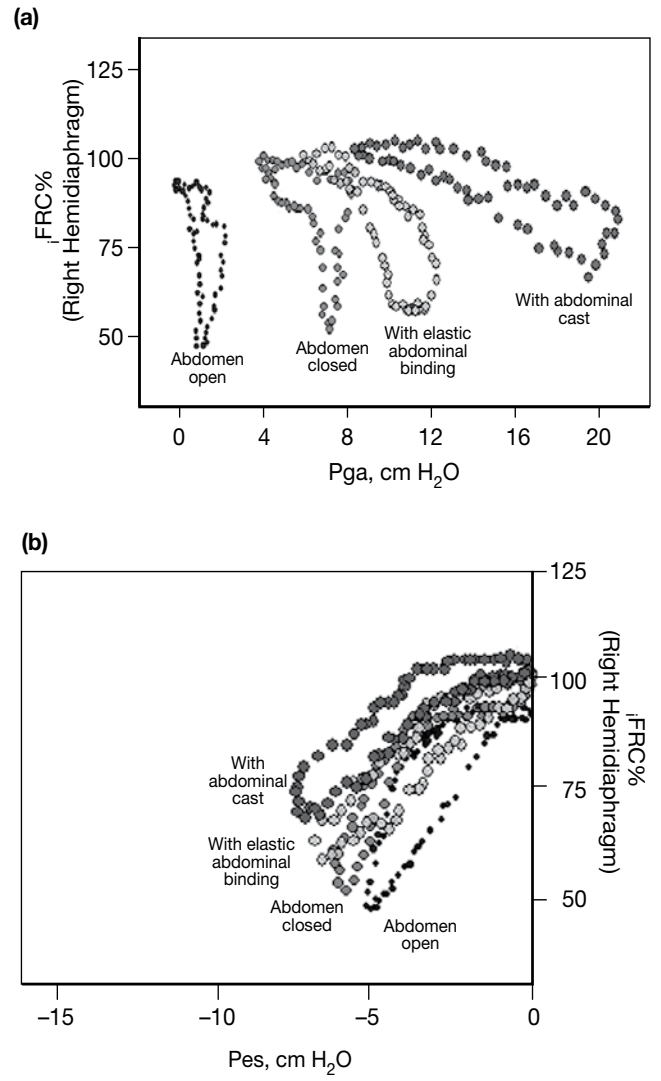

Figure 2. a, relationship between stimulation-induced gastric pressure (Pga) and length of the right hemidiaphragm (expressed as a percentage of the length at functional residual capacity at baseline [$_{i}$FRC%]) during muscle contraction and relaxation in one of the animals and under the different experimental conditions. The gastric pressure is shown here using its absolute values (explaining the progressive displacement to the right as the resting abdominal pressure increases). Diaphragmatic activity (time sequence in a clockwise direction, with contraction on the right side of each loop and relaxation on the left), in contrast, is shown as the difference between the baseline and maximum values. b, relationship between stimulation-induced esophageal pressure (Pes) and length of the right hemidiaphragm (animal and conditions as above). In this case, the initial pressure has been normalized to 0.

increases in the resting length with respect to the $_{i}$FRC led to a fall in the efficacy of contraction (Figure 3).

Discussion

This study confirms that, in animals anesthetized with pentobarbital, the diaphragmatic response decreases slightly after abdominal surgery and improves after abdominal binding with either an elastic bandage or a rigid cast. The improvement appears to be due mainly to changes in muscle length, with optimal contraction occurring very close to the physiologic situation of the respiratory system at rest (FRC).

The contractile response of the diaphragm is known to depend on the lung volume at which maximum contraction occurs, whether voluntary[11,12] or induced by stimulation.[12] The greater the lung volume, the lower the pressure. This phenomenon has been related to the initial muscle length at which contraction occurs. In order to minimize the influence of lung volume on the muscle response in the present study, stimulation was always performed at the end of expiration and with the airway occluded. The strength of the diaphragm can also be affected by the spatial conformation of its curvature and the thoracoabdominal configuration,[12-15] though the degree of influence will be less. Specifically, the abdominal component appears to be as important as that of the thoracic cage, although the effect of the thoracic component predominates in respiratory diseases. The influence of the abdominal components on the strength that the diaphragm can develop also appears to be related mainly to the initial length of the muscle. The placement of a rigid cast around the abdomen is known to increase the mechanical (pressure) and electrical (electromyographic signal) response of the diaphragm to stimulation.[3,16-18] However, this phenomenon has not been studied in detail from the point of view of the characteristics of the contraction itself. It is believed that increased stiffness of the abdominal wall means that less of the efficacy of diaphragmatic contraction is lost to displacement of the abdominal viscera and wall.[19,20] It has also been suggested that a change in the initial length of the diaphragm may be used to optimize contraction. Finally, a further suggestion is that abdominal binding would delay descent of the diaphragm by limiting expansion of that cavity,[18] thus reducing the speed of diaphragmatic contraction. A technique such as sonomicrometry is needed to record variations in resting muscle length, the true degree of shortening, and the speed of contraction; this technique enables these variables to be evaluated directly.

This study confirmed that upper abdominal surgery decreased the contractile capacity of the diaphragm. It is known that this has major clinical and physiologic consequences, such as the onset of basal atelectasis, pneumonia, and decreased FRC and vital capacity.[21-24]

Table
Mean (SD) Values for Pressure, Muscle Shortening, and Speed of Contraction Before and After Abdominal Binding With an Elastic Bandage or Rigid Cast, and With Increasing Values of Added Pressure on the Anterior Abdominal Wall

	Pga, cm H_2O	Pdi, cm H_2O	Global Shortening, $_{i}$FRC%	RHD Shortening, $_{i}$FRC%	LHD Shortening, $_{i}$FRC%	Global Speed, $_{i}$FRC%/s
Baseline	4.8 (0.5)	13.1 (1.3)	–	–	–	–
After closure of laparotomy	4.2 (0.3)[a]	12.1 (2.0)	57 (5)	57 (8)	56 (7)	3.8 (0.2)
Elastic bandage	6.3 (0.9)[b]	15.4 (1.8)[c]	49 (5)[c]	49 (8)[c]	48 (7)[c]	3.5 (0.2)[c]
Cast with no additional abdominal pressure	12.6 (1.5)[b]	20.2 (2.3)[b]	39 (6)[b]	44 (9)[c]	35 (8)[b]	3,0 (0,3)[b]
Cast + P1	15,4 (1,7)[b]	23.1 (2.4)[b]	20 (6)[b]	21 (7)[b]	19 (7)[b]	3.1 (0.2)[b]
Cast + P2	18.3 (2.0)[b]	26.3 (3.1)[b]	20 (6)[b]	21 (8)[b]	19 (6)[b]	3.2 (0.3)[b]
Cast + P3	13.1 (1.5)[b]	21.6 (2.3)[b]	17 (5)[b]	17 (6)[b]	17 (5)[b]	3.1 (0.2)[b]
Cast + P4	10.9 (1.2)[b]	19.5 (2.1)[b]	14 (6)[b]	15 (6)[b]	14 (6)[b]	3.1 (0.2)[b]

Abbreviations: $_{i}$FRC%, percentage of the initial length of the muscle at functional residual capacity; LHD, left hemidiaphragm; P1, P2, P3, and P4, instrumental increases in abdominal pressure of 20, 40, 60, and 70 cm H_2O, respectively; Pdi, transdiaphragmatic pressure; Pga, gastric pressure induced by supramaximal electric stimulation; RHD, right hemidiaphragm.

[a] $P<.05$ with respect to baseline (presurgery). [b] $P\leq.01$ with respect to the measurement after laparotomy. [c] $P<.05$ with respect to the measurement after laparotomy.

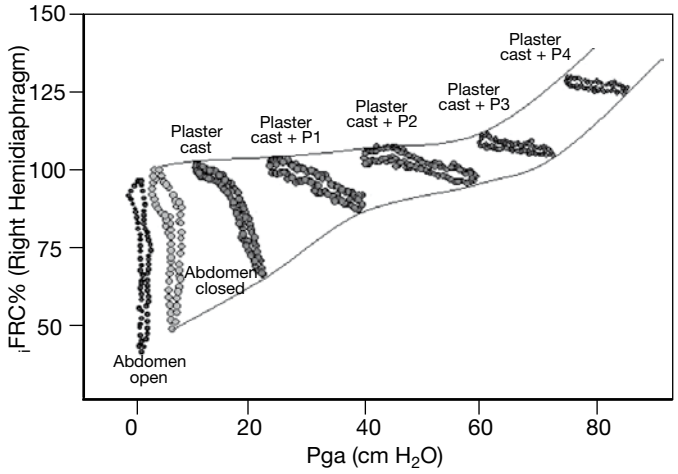

Figure 3. Relationship between stimulation-induced gastric pressure (Pga) and initial length of the right hemidiaphragm ($_{i}$FRC%), during muscle contraction and relaxation in another of the animals. Once again, the Pga is shown as absolute values. The different conditions here include the application of added pressure (P1, P2, P3, and P4: instrumental increase in abdominal pressure of 20, 40, 60, and 70 cm H_2O, respectively), with successive lengthening of the muscle, and observation of an optimal length (L_0, close to functional residual capacity). Below and above this length, contraction loses efficacy. The lines show the prediction for *n* elongations between the true values included in the study.

It is also believed that this dysfunction is not linked to an accidental lesion of the muscle or its manipulation, but rather that it is attributable mainly to extrinsic factors: pain and muscle inhibition via visceral afferent nerves are 2 factors that have been suggested.[25,26] Whatever the cause, contractile muscle shortening appears to decrease after laparotomy,[22] an effect that can persist up to the tenth day,[22] although some authors have not observed this phenomenon.[21] An additional factor seems to be the slight loss of stiffness of the abdominal wall after incision and suture. In our study, we were unable to establish the cause of the functional loss, though some factors, such as limitation due to abdominal pain, could be excluded, given that although additional analgesia was not administered to the animals, supramaximal stimulation lacks any voluntary component. The implicit absence of sonomicrometry prior to surgery meant that the influence of the loss of wall stiffness on resting muscle length after the operation could not be assessed. Both this mechanism and the above-mentioned reflex inhibition could therefore be responsible for the deterioration in muscle function. However, the subsequent improvement in contractility after relatively loose binding would appear to indicate that abdominal wall stiffness does play a role.

We observed that both the elastic bandage and the plaster cast led to lengthening of the diaphragm. This enabled the muscle to generate greater pressures with lesser degrees of shortening (contraction). Previous studies using stimulation of the abdominal muscles have shown that their contraction improved the length of the diaphragm and enabled it to generate higher pressures.[27] The rigid cast has a similar but less marked effect.[3,16-18] Our study confirmed that the improvement occurred even with relatively loose binding with an elastic bandage and that this is at least partially due to a more favorable initial length of the muscle. The changes observed in the speed of shortening of the muscle may also play a part.[18]

This study also confirmed that further increases in the initial length of the diaphragm enabled successively better results to be achieved, until an optimal length is reached, after which further increases in the resting length of the muscle do not achieve higher pressures. In other words, the study also corroborated the existence in vivo of an optimal length at which the muscle works most efficiently. This agrees with previous studies performed in vitro with muscle strips.[28-30]

With regard to the potential limitations of this study, it should be taken into account that the gastric signal is more valuable than the esophageal signal for the evaluation of diaphragmatic activity, as Pes can be influenced by esophageal contractions caused by the stimulation itself.[18] That interference, which is often accepted in this type of study, could also have indirectly affected the Pdi, as this is a derived variable.

Concerning the possible effect of anesthesia on muscle mechanics, pentobarbital is know to be able to reduce the activity of the respiratory muscles slightly.[31] However, it is considered that this effect is minor,[32] does not modify the relative contribution of the different respiratory muscles,[32] and is much smaller than the effect of alternative inhaled anesthetics.[33] For this reason, the type of sedation used in the present study has been used extensively in the investigation of muscle mechanics.[7-9,33,34] In addition, care was taken to ensure that sedation was stable in all those situations in which abdominal wall stiffness was modified.

There are several clinical implications of our findings. First, diaphragmatic stimulation was confirmed as a useful technique for investigation of the contractile characteristics of the muscle, but only when a series of factors are controlled; these factors are not only thoracic but also abdominal, as orthopedic appliances and tight clothing can affect the response. This should also be taken into account when voluntary maneuvers of muscle contraction or magnetic stimulation of the diaphragm is performed,[35] as the abdominal factor is often underestimated in these situations. Furthermore, we may conclude that abdominal surgery per se has relatively little effect on diaphragmatic contractility in healthy animals (and probably in healthy human individuals). However, the slight loss of function could be of considerable importance in operations performed on patients with associated lung disorders such as chronic obstructive pulmonary disease or an exacerbation of asthma. In these cases, the diaphragm will already be in a poor position for contractile effect and the resistances against which the muscle must work will be greater due to the specific mechanics of the disease (hyperinflation) and the possible accumulation of secretions. When this occurs, the use of abdominal binding, in addition to correct postoperative analgesia, may be considered for its beneficial effect when seeking to achieve a good length of the diaphragm.

Finally, consideration should be given the possibility of improving contraction by increasing the resting length of the diaphragm to a little above the length at FRC. This could be of interest in patients with chronic obstructive pulmonary disease, in whom the changes in thoracic mechanics have already produced flattening and shortening of the muscle. Some means of improvement in abdominal compliance could perhaps help us to compensate for hyperinflation and avoid dynamic air trapping, particularly in situations of exertion or in exacerbations. In fact, some studies have demonstrated that an abdominal corset produces higher respiratory pressures, and some authors even recommend their use when these pressures are being measured[10,16]; others, however, criticize this method as they believe that it leads to overestimation of the true functional capacity of the diaphragm.[36]

In conclusion, it should not be forgotten that the contractile capacity of the diaphragm depends not only on the muscle and the characteristics of the thoracic cage and organs, but also on the abdominal cavity and its contents. Both surgery and certain external factors (elastic or rigid binding and, perhaps, clothing) can alter the characteristics of the abdomen and its contents and affect muscle function; this is of particular importance in patients with respiratory diseases.

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