Hyperinflation using pressure support ventilation improves secretion clearance and respiratory mechanics in ventilated patients with pulmonary infection: a randomised crossover trial

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Question: Is ventilator-induced hyperinflation in sidelying more effective than sidelying alone in removing secretions and improving respiratory mechanics in ventilated patients with pulmonary infection? **Design**: Randomised crossover trial with concealed allocation and intention-to-treat analysis. **Participants**: 30 mechanically ventilated patients with pulmonary infection in an adult intensive care unit. **Intervention**: The experimental intervention was 30 minutes of ventilator-induced hyperinflation using pressure support ventilation in sidelying; the control intervention was 30 minutes of sidelying. Participants received both interventions on the same day, with a five-hour washout period between them. **Outcome measures**: Secretion clearance was measured as sputum volume retrieved during the intervention. Respiratory mechanics were measured as static compliance and total resistance of the respiratory system before and after the intervention. **Results**: The experimental intervention cleared 1.3 ml (95% CI 0.5 to 2.2) more secretions than the control. After ventilator-induced hyperinflation in sidelying, respiratory compliance had increased 4.7 ml/cmH_2O (95% CI 2.6 to 6.8) more than in sidelying alone. There was no difference in total resistance of the respiratory system between the interventions (mean difference 0.3 cmH_2O/l/s, 95% CI –0.8 to 1.3). **Conclusion**: The application of hyperinflation using pressure support ventilation in mechanically ventilated patients with pulmonary infection improves secretion clearance and increases static compliance of the respiratory system. **[Lemes DA, Zin WA, Guimarães FS (2009) Hyperinflation using pressure support ventilation improves secretion clearance and respiratory mechanics in ventilated patients with pulmonary infection: a randomised crossover trial. *Australian Journal of Physiotherapy* 55: 249–254]**

Key words: Randomized controlled trial, physiotherapy, intensive care, pulmonary ventilator, respiratory mechanics

Introduction

In mechanically-ventilated patients, augmented mucus production and impaired mucociliary clearance are common characteristics that lead to an increased risk of mucus retention in the airways as well as to the development of pulmonary infection and obstructive atelectasis (Konrad et al 1994). Therefore, respiratory physiotherapy intervention (positioning, postural drainage, percussion, vibration, endotracheal suctioning, and manual hyperinflation) is used routinely in the management of ventilated patients in the intensive care unit to prevent mucus retention and pulmonary complications, improve oxygenation, and re-expand collapsed areas (Clini and Ambrosino 2005).

The use of positive pressure devices has been part of physiotherapy intervention since intermittent positive pressure breathing was introduced in clinical practice (Motley and Werko 1947). In intensive care settings, the use of positive pressure by physiotherapists includes manual hyperinflation (bagging or bag squeezing), which has been shown to increase oxygenation and mobilise excessive bronchial secretions, and to reinflate collapsed areas (Berney and Denehy 2002, Berney et al 2004, Choi and Jones 2005, Hodgson et al 2007, Blattner et al 2008). It involves the application of a slow, deep inspiration using a manual resuscitation bag applied to the endotracheal or tracheostomy tube, followed by an inspiratory pause (1–2 seconds), and a rapid release of the resuscitation bag, combined with thoracic vibration, to improve expiratory flow and stimulate a cough (Clement and Hubsch 1968). An alternative method of performing pulmonary hyperinflation uses the mechanical ventilator. Although there is evidence that positive pressure interventions such as continuous positive airway pressure and intermittent positive pressure breathing can improve lung expansion and mobilise secretions in the airway (Denehy and Berney 2001), there are few studies examining ventilator-induced hyperinflation as a physiotherapy intervention in intensive care (Berney and Denehy 2002, Berney and Denehy 2003, Savian et al 2006). To our knowledge, there are no studies investigating secretion clearance and respiratory mechanics in patients undergoing hyperinflation using pressure support ventilation. The use of pressure support ventilation to achieve hyperinflation may be beneficial, since it is comfortable for the patient and the pressure limit avoids excessive pressures. Therefore, the research question for this study was:

> Is ventilator-induced hyperinflation using pressure support ventilation in sidelying more effective than sidelying alone in removing secretions and improving respiratory mechanics in ventilated patients with pulmonary infection?

Method

Design

This was a randomised, crossover trial in which patients were their own control. Participants were recruited from patients admitted to an 11-bed intensive care unit at a tertiary referral hospital. The allocation sequence was prepared by an investigator who was not involved in recruitment, intervention, or measurement. Randomisation was computer generated in 3 blocks of 10 and stored in sealed, opaque envelopes that were opened by the physiotherapist delivering the intervention on the day. The experimental intervention was 30 minutes of ventilator-induced hyperinflation using pressure support ventilation in sidelying and the control intervention was 30 minutes of sidelying. All participants received both interventions on the same day, with a five-hour washout period between them. Secretion clearance was measured during both interventions while respiratory mechanics were measured before and after (Figure 1). The same physiotherapist, who was not blinded to intervention allocation, delivered both interventions and recorded all measurements.

Participants

Mechanically ventilated patients were included if they had a medical diagnosis of pulmonary infection (defined according to laboratory and radiological criteria) and hypersecretion (defined as the interval between tracheal suctioning < 2 hours). All participants were initiating all breaths spontaneously. They were excluded if they had haemodynamic instability (defined as a heart rate > 130 bpm and mean arterial pressure < 60 mmHg), used vasopressor drugs, had acute bronchospasm, had acute respiratory distress syndrome, had atelectasis (identified by an independent radiologist), were immediately post neurosurgery, had an untreated pneumothorax, had lung haemorrhage, or were unable to be positioned in sidelying.

Intervention

The experimental intervention consisted of 30 minutes of ventilator-induced hyperinflation in sidelying. Initially, participants were mechanically ventilated in the volume-induced mode, with a tidal volume of 8 ml per kilogram of body weight, inspiratory flow of 60 litres per minute (square wave), with hyperinflated cuff, positioned in a supine 30-degree head-up position, and underwent tracheal aspiration. Inspiratory oxygen fraction and positive end-expiratory pressure remained unchanged. Next, they underwent 3 sighs with a two-fold increase in tidal volume (Mead and Collier 1959). Participants were then positioned in sidelying with the more affected lung, verified on chest X-ray, uppermost. The mechanical ventilation was changed to the pressure support mode with a peak pressure of 40 cmH_2O to apply hyperinflation. After 30 minutes, ventilation was returned to the original settings, participants were repositioned in the supine 30-degree head-up position and underwent tracheal aspiration and another 3 sighs with a two-fold increase in tidal volume.

Physiological parameters (heart rate, mean arterial pressure, oxygenation, airway pressures, tidal volume, and respiratory rate) were recorded before, during, and after the experimental intervention to assess safety. Mean arterial pressure in mmHg, heart rate in bpm, and oxygenation were collected using a multiparameter monitor[a]. Tidal volume in ml and respiratory rate in bpm were collected from the ventilator display[b] and used to calculate minute ventilation. Mean, plateau, and peak airway pressures in cmH_2O were also collected from the ventilator display. Adverse events were defined as heart rate > 140 bpm, mean arterial pressure < 60 mmHg, and/or arterial oxygen saturation < 90%.

The control intervention consisted of 30 minutes of sidelying without ventilator-induced hyperinflation or any other physiotherapy intervention.

Outcome measures

The primary outcome was secretion clearance and secondary outcomes were respiratory mechanics. Secretion clearance was measured as sputum volume in ml. At the 15th and 30th minutes, the patients underwent artificial airway suctioning and secretions were collected in a sputum trap attached to the closed suction system. Then, sterile saline solution was flushed through the suction tubing into the trap to remove any secretions remaining in the catheter. The volume of sputum was calculated by summing the two measures and subtracting the volume of the sterile saline.

Respiratory mechanics were measured as static compliance and total resistance of the respiratory system. Tidal volume in ml, respiratory rate in bpm, and plateau, peak and mean airway pressures in cmH_2O were collected from the ventilator display and used to calculate static compliance in ml/cmH_2O and total resistance in $cmH_2O/l/s$ of the respiratory system. According to the interrupter technique (Bates et al 1985), a 2 s inspiratory pause (Lucangelo et al 2005) was applied and waveforms were examined to ensure a flat plateau for reliable measurements. The mean of five readings was used as the representative value for each variable.

Data analysis

According to Hodgson et al (2000), power calculation indicated that 20 participants would provide sufficient power (80%) to detect a difference of 57% in sputum volume, assuming a standard deviation of 62% and significance of 0.05. Results are expressed as mean (SD), mean (SD) differences within interventions and mean differences (95% CI) between interventions. Two-way repeated-measures analysis of variance was used to examine the statistical significance of between-group differences in respiratory mechanics. Paired t-test was used to examine the statistical significance of between-group differences in sputum volume. Changes in haemodynamics, oxygenation, ventilation and airway pressures were examined using descriptive statistics. The significance level was set at $p = 0.05$.

Results

Flow of participants, therapists, centres through the trial

Recruitment and data collection were carried out between April 2006 and July 2007. Thirty mechanically ventilated patients, with medical diagnosis of pulmonary infection participated. All participants received both interventions and completed all measurements (Figure 1). Participants' characteristics are given in Table 1. The participants were similar in terms of respiratory mechanics before intervention (Table 2).

A single physiotherapist with 10 years experience in critical care settings delivered both the experimental and control interventions.

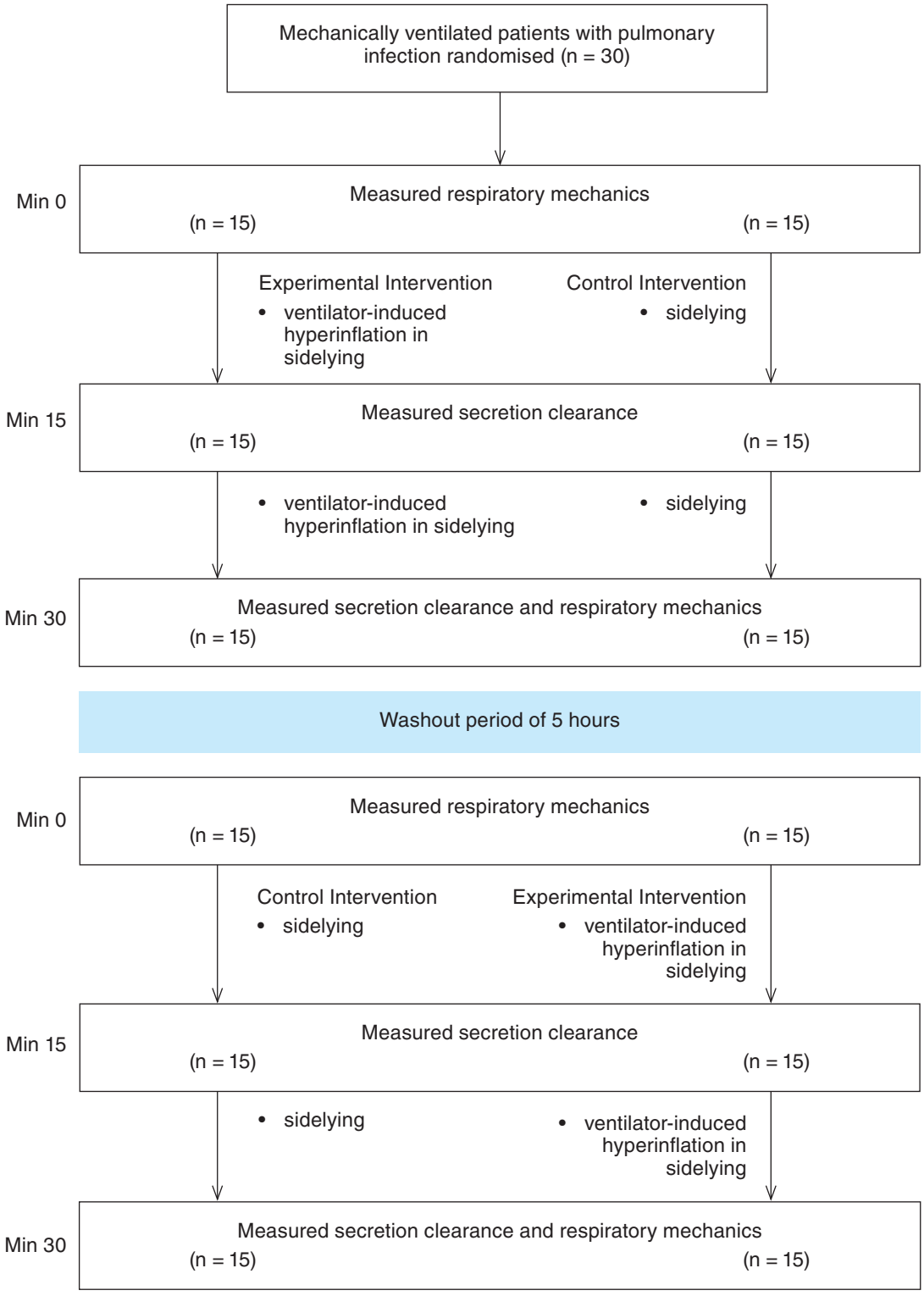

Figure 1. Design and flow of participants through the trial.

Table 1. Characteristics of participants.

Characteristic	(n = 30)
Age (*yr*), mean (SD)	61 (16)
Gender, n males (%)	19 (63)
PEEP (cmH_2O), mean (SD)	6.9 (1.2)
PaO_2/FiO_2, mean (SD)	322 (105)
APACHE II, mean (SD)	13.7 (6.2)
Intensive care length of stay (*days*), mean (SD)	13 (9)
Ramsay Scale, median (IQR)	3 (3–4)
Diagnosis, n (%)	
Ventilator-associated pneumonia	23 (77)
Community-acquired pneumonia	4 (13)
Aspiration pneumonia	3 (10)
Upper abdominal surgery	4 (13)
Pulmonary oedema	1 (3)
Pulmonary embolus	1 (3)
Stroke	10 (33)
Convulsions	2 (7)
Septic shock	7 (23)
Urinary tract infection	2 (7)
Intracerebral tumor	1 (3)
Congestive heart failure	1 (3)

PEEP = positive end expiratory pressure; PaO2/FiO2 = arterial PO_2-to-inspired oxygen concentration ratio; Cst,rs = static compliance of respiratory system; Rrs = total resistance of respiratory system; APACHE II = Acute Physiology and Chronic Health Disease Classification System II

There was only one centre involved in this trial. The trial was carried out in an 11-bed intensive care unit at a tertiary referral hospital (Hospital Central da Polícia Militar do Estado do Rio de Janeiro, Rio de Janeiro, Brazil). This intensive care unit has a throughput of 234 patients per year with 65% managed with mechanical ventilation.

Compliance with trial method

Participants coped well with the experimental intervention. No individual participant had a sufficient change in heart rate, mean arterial pressure, or oxygenation to meet our definition of an adverse event. Although mean arterial pressure decreased significantly ($p < 0.001$) during the experimental intervention, the magnitude of the change was only 4 mmHg (4%) and was therefore clinically unimportant. As expected, mean airway pressure and tidal volume increased and respiratory rate decreased (all $p < 0.001$ for within-group changes), with no overall difference in minute ventilation (Table 3).

Effect of intervention

Group data for all outcomes for the experimental and control interventions are presented in Table 2 while individual data are presented in Table 4 (see eAddenda for Table 4). The experimental intervention cleared 1.3 ml (95% CI 0.5 to 2.2, $p = 0.004$) more secretions than the control. After ventilator-induced hyperinflation in sidelying, respiratory compliance had increased 4.7 ml/cmH_2O (95% CI 2.6 to 6.8, $p < 0.001$) more than in sidelying alone. Respiratory resistance increased only 0.3 cmH_2O/l/s (95% CI –0.8 to 1.3, $p = 0.62$) more after the experimental than the control intervention, without statistical significance. There was no order effect for any outcome.

Discussion

This is the first study to investigate the use of pressure support ventilation to hyperinflate the lung. The results showed that a 30-minute application of ventilator hyperinflation in sidelying is more efficient in facilitating secretion clearance than 30 minutes of side-lying in mechanically ventilated hypersecretive patients. This finding was supported by the larger increase in respiratory compliance as well as the higher volume of mucus secretion in the experimental intervention.

Our results are consistent with previous studies that evaluated the use of a mechanical ventilator (Berney and Denehy 2002, Savian et al 2006) to produce lung hyperinflation using the volume-controlled mode. In the present investigation, however, pressure support ventilation

Table 2. Mean (SD) of interventions, mean (SD) difference within interventions, and mean (95% CI) difference between interventions.

Outcome	Interventions				Difference within interventions		Difference between interventions
	Pre-test		Post-test		Post-test minus Pre-test		Post-test minus Pre-test
	Exp (n = 30)	Con (n = 30)	Exp (n = 30)	Con (n = 30)	Exp	Con	Exp minus Con
Secretion clearance							
Sputum volume *(ml)*			4.1 (2.6)	2.8 (2.0)			1.3 (0.5 to 2.2)
Respiratory mechanics							
Cst,rs *(ml/cmH_2O)*	47.8 (11.4)	49.0 (12.8)	54.4 (13.8)	50.9 (13.6)	6.6 (6.7)	1.9 (2.5)	4.7 (2.6 to 6.8)
Rrs *(cmH_2O/l/s)*	15.5 (4.7)	15.8 (4.6)	16.0 (4.6)	16.0 (4.8)	0.5 (1.7)	0.2 (1.9)	0.3 (–0.8 to 1.3)

Exp = experimental intervention; Con = control intervention; Cst,rs = static compliance of respiratory system; Rrs = total resistance of respiratory system. Shaded row = primary outcome

Table 3. Mean (SD, range) physiological parameters before, during, and after the experimental intervention.

Physiological parameters	Before (0 min)	During (15 min)	During (30 min)	After (35 min)
MAP *(mmHg)*	93 (14, 67–117)	90 (16, 67–124)	89 (17, 57–120)	91 (15, 61–117)
MPaw *(cmH2O)*	11 (2, 8–13)	13 (2, 8–18)	13 (3, 8–19)	11 (2, 7–15)
HR *(bpm)*	92 (18, 56–125)	92 (18, 57–124)	93 (18, 61–122)	92 (17, 59–125)
V'E *(l/min)*	9.8 (2.5, 6–18)	9.8 (3.7, 5–22)	8.9 (3.3, 5–19)	9.5 (2.6, 6–16.5)
VT *(ml)*	557 (88, 447–750)	1337 (430, 418–2569)	1330 (452, 551–2718)	562 (90, 447–769)
RR *(bpm)*	17 (3, 13–24)	8 (3, 4–15)	7 (3, 4–14)	17 (3, 12–25)

MAP = mean arterial pressure; MPaw = mean airway pressures; HR = heart rate; V'E = minute ventilation; VT = tidal volume; RR = respiratory rate.

was used to hyperinflate the lung, assuming that it may avoid excessive pressures during therapy and improve patient-ventilator synchrony (MacIntyre 1986), thus promoting a feeling of comfort during the manoeuvre. The increase in transpulmonary pressure by therapeutic hyperinflation leads to a higher lung volume, improving collateral ventilation and, consequently, the ventilation of obstructed alveolar units. Expiratory flow rate increases due to the greater passive elastic recoil of the lung. This effect improves gas-liquid interaction, and consequently, mucus mobilisation from peripheral to central airways (Selsby and Jones 1990) increasing respiratory compliance, as hypothesised by Winning et al (1975).

A minimum delivered tidal volume of at least one-third of the predicted inspiratory capacity (1/3 × 50 ml/kg) (approximately 1167 ml in a 70 kg adult patient) has been suggested to promote therapeutic effects during lung expansion manoeuvres (AARC 2003). Although it was not possible to calculate participants' exact weights in the present study, the mean tidal volume achieved during hyperinflation (mean 1331 ml, SD 451) could be considered high enough to promote the desired effects in our patients.

In line with the results from Hodgson et al (2000), who demonstrated a higher mucus clearance after manual hyperinflation in side-lying compared to side-lying positioning, our experimental intervention cleared more secretions than the control. Since sputum volume was not large during the control (2.8 ml) or experimental intervention (4.1 ml), the mean difference between them was only 1.3 ml. This was slightly smaller (in both absolute and relative terms) than the effect on sputum volume seen in the study by Hodgson and colleagues (2000). This difference may reflect the fact that their intervention also included the 2 s inspiratory hold traditionally incorporated in 'manual hyperinflation'. Nevertheless, the effect on sputum volume we identified represents a clinically relevant increment of 49% in sputum clearance. Considering that airway suctioning was performed before the interventions, this sputum volume difference could be attributed to mucus clearance from intermediate and/or peripheral airways, improving respiratory compliance.

There was no significant difference in the change in respiratory resistance between the two interventions, since there was a wide range of responses. This variability in response to intervention may be due to different patterns of mucus distribution along the airways among the patients. In some patients, the mucus movement from peripheral to central airways without elimination by tracheal aspiration could increase respiratory resistance, since the airway generations that contribute the highest resistance are the central ones (Weibel 1963). Another possible explanation is that bronchial hyperreactivity and transient bronchoconstriction induced by tracheal aspiration are factors that could contribute to increased respiratory resistance in some patients, overlapping the deobstructive effect of the interventions.

According to Zeppos et al (2007), many studies evaluating adverse physiological changes during physiotherapy intervention in intensive care units have methodological limitations, thus rendering the results inconclusive. In our study no adverse events were found during ventilator hyperinflation, probably because the use of a mechanical ventilator allows better control of ventilatory parameters, ensuring total expiration before the next respiratory cycle and avoiding air trapping and intrapulmonary pressure increases (Berney and Denehy 2002). Since the higher tidal volume used in hyperinflation manoeuvres tends to increase mean airway pressure leading to adverse haemodynamic effects, the protocol used in this study was intended to minimise this by using assisted ventilation. As anticipated, the patients automatically reduced their respiratory rate and maintained their minute ventilation unchanged, which attenuated the rise in airway pressure. Although the manoeuvre increased mean airway pressure somewhat, the observed haemodynamic responses (as indicated by the change in mean arterial pressure) were not clinically important (Hollenberg et al 2004). Given the unchanged minute ventilation and absence of apnoea episodes in our study, another possible advantage of using hyperinflation by means of assisted ventilation is to avoid the adverse effects of hyperventilation.

Regarding the limitations of the study, physiological parameters could have been measured during the control intervention, allowing between-interventions comparison. Moreover, respiratory mechanics could have been measured at least one hour after the interventions, and all measurements could have been done by a blinded assessor. Clinically relevant outcomes (such as time to resolution of infection, time to extubation, time of mechanical ventilation

and intensive care length of stay) were not recorded and should be investigated further.

The results of the current study are similar to those of others that evaluated the use of mechanical ventilator. However, our study introduced a new ventilation modality to achieve the desired goals. Different ventilator hyperinflation protocols should be compared to determine the most advantageous modality in terms of physiological and clinical outcomes. Finally, ventilator hyperinflation by pressure support ventilation increases sputum clearance and static compliance of the respiratory system in mechanically ventilated patients with pulmonary infection. ■

Footnotes: [a]Millennia 3500, Invivo, Orlando, FL, USA, [b]Vela, Infrasonics, San Diego, CA, USA

eAddenda: Table 4 available at AJP.physiotherapy.asn.au

Ethics: The Clementino Fraga Filho University Hospital Ethics Committee approved this study. Written informed consent was obtained from the patients' next of kin before the study began.

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