

Assessment of lung volumes in children and adolescents: comparison of two plethysmographic techniques

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Summary

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Thoracic gas volume (V_{tg}) can be measured with body plethysmography by either repetitive panting or one single inspiratory effort against a shutter occluding the airways. The panting technique is preferred, but may be demanding. We aimed to assess the precision of these two methods and the degree of agreement between them. V_{tg} and functional residual capacity (FRC) were measured in 155 subjects with a standard, commercially available plethysmograph, acting as a variable-pressure, constant-volume device when V_{tg} is determined. Total lung capacity (TLC) and residual lung volume (RV) were calculated subsequent to a full vital capacity manoeuvre. For non-asthmatic healthy subjects, the standard deviations (SD) of the differences between two replicate measurements of FRC, TLC and RV were respectively 0.16, 0.13 and 0.14 litres with the panting technique, and 0.18, 0.18 and 0.23 litres with the single inspiratory effort technique. In percentage of the respective lung volumes, the corresponding 1.96 SDs were 20%, 8% and 40% with the panting technique and 23%, 12% and 67% with the single inspiratory effort technique. Between the two techniques, 95% limits of agreement were 21% for FRC, 11% for TLC and 58% for RV. The variability of V_{tg} and FRC accounted for most of the variability of TLC and RV. In conclusion, the panting and the single inspiratory effort technique produced results that were comparable in magnitude, however with a better precision with the panting technique. The single inspiratory effort technique can be used as an alternative if the panting technique fails.

Introduction

Changes in static lung volumes are important outcomes of many different types of lung disease and dysfunction at all ages (Gibson, 1996; Bancalari & Clausen, 1998). Lung volumes refer to various defined subdivisions of gas-containing spaces in the lungs, such as functional residual capacity (FRC), total lung capacity (TLC) and residual lung volume (RV). The mechanisms that set these volumes are different and vary with age and disease conditions (Leith & Brown, 1999). Thoracic gas volume (V_{tg}) is defined as the volume of intrathoracic gas at the time the airway is occluded when lung volumes are measured in a body plethysmograph. V_{tg} is measured by making the test subject perform repetitive respiratory efforts (panting) against a shutter occluding the airways at the end of a tidal expiration (DuBois *et al.*, 1955; Coates *et al.*, 1997). Changes in pressures

measured at the mouth are assumed to reflect corresponding changes in pressures of the alveoli. The estimates of V_{tg} are based on Boyle-Mariotte's law.

Body plethysmography with a panting frequency below 1 Hz is the recommended method to determine V_{tg} in subjects with airflow limitation (Shore *et al.*, 1983; Quanjer *et al.*, 1993). Children may have difficulties with this standard panting manoeuvre, and an alternative method has been developed, based on one single inspiratory effort against the shutter (DuBois *et al.*, 1955). Clinical studies reporting on the repeatability of data obtained with the panting and the single inspiratory effort techniques and the degree of agreement between the two are scanty, particularly in paediatric populations (Desmond *et al.*, 1988). The main objective of this study was to provide such data for these two techniques in children and adolescents with minimal experience with lung function testing.

Methods

Subjects and study design

The study was part of an investigation examining pulmonary outcome of extreme preterm delivery (Halvorsen et al., 2004). Preterms consisted of two population-based cohorts of subjects with gestational age ≤ 28 weeks or birth weight ≤ 1000 g, born within a health region in western Norway in the years 1982–1985 (the adolescents) and 1991–1992 (the 10 year olds). For each preterm, the temporally nearest term-born subject of the same gender with birth weight between 3 and 4 kg (within the Norwegian 10th–90th percentiles) was recruited as control (Skjaerven et al., 2000). The Regional Ethics Committee approved the study, and informed written consent was obtained from participating subjects and parents.

The basic characteristics of the study population are given in Table 1, including the mean forced vital capacity (FVC) and forced expired volume in 1 s (FEV_1), expressed as percentages of predicted (Polgar & Promadhat, 1971). All but two subjects were Caucasians and all were native Norwegians. All subjects and their parents completed the core questions from the International Study on Asthma and Allergy in Childhood (ISAAC, 1998). A methacholine provocation test (Nieminen et al., 1988) was carried out in all but nine participating subjects, i.e. in those who could cope and had FEV_1 higher than 65% of the predicted after asthma medication had been withheld for 24 h. Asthma was defined by a history of wheeze within the preceding 12 months and a positive response to methacholine (Global Initiative for Asthma, 2002). No subjects were examined within 2 weeks of a respiratory tract infection or an asthma incident.

Subjects were examined twice within 2 weeks in 2001–2002. All 10 year olds completed a panting and a single inspiratory effort manoeuvre on each of the two test-days, whereas all adolescents performed either a panting or a single inspiratory effort manoeuvre on each test-day, the sequence being randomized. Repeatability of the panting and the single inspiratory effort technique was assessed with data from the

10 year olds ($n = 69$), comparing results obtained with the panting technique on day 1 and 2, and comparing results of the single inspiratory effort technique on day 1 and 2.

Agreement between the two techniques was assessed with data from all participating subjects ($n = 155$). To ensure a similar degree of familiarity with both techniques in both age groups, results obtained on the first day of testing were selected to represent the 10 year olds.

Lung function measurements

Lung volumes were determined in accordance with the guidelines of the European Respiratory Society (Coates et al., 1997) with a combined pressure-flow plethysmograph, Vmax Autobox 6200 (SensorMedics Corporation, 2000). The plethysmograph functions as a variable-pressure, constant-volume device while measuring V_{tg} . Flow was measured with a mass flow sensor. Calibration of the flow sensor and the plethysmograph was performed prior to each test in accordance with automated procedures and the instructions given by the manufacturer (SensorMedics Corporation, 1996). A bacterial filter (MicroGard, SensorMedics inc., Yorba Linda, USA) with an attached mouthpiece was used. Subjects were tested seated in an upright position with the face pointing straight forward, supporting the cheeks in their hands and wearing a nose-clip.

After closing the door and a period of relaxed tidal breathing to allow for thermal stabilization and familiarization with the test-situation, a baseline level of FRC was established from at least four stable tidal breaths. With the panting technique, test subjects were coached to pant gently with a frequency of about 1 Hz (Shore et al., 1983). The shutter closed at the end of a tidal expiration whereupon a series of at least four panting movements were done against it, recording the corresponding pressure-volume loops. After opening of the shutter, the test subjects made two to three tidal breaths before performing a full inspiratory manoeuvre to TLC followed by a full expiratory manoeuvre to RV. From each acceptable pressure-volume loop,

Table 1 Basic characteristics of the study population.

	Ten year olds		Adolescents	
	Preterms ($n = 35$)	Controls ($n = 35$)	Preterms ($n = 46$)	Controls ($n = 46$)
Females/males	22/13	22/13	21/25	21/25
No. of asthmatics	10/35	2/35	9/46	5/46
No. of smokers	0	0	15/46	14/46
Age (years)	10.5 (0.4)	10.6 (0.4)	17.6 (1.2)	17.8 (1.2)
Height (cm)*	140.1 (7.9)	144.7 (6.3)	169.7 (7.9)	172.9 (7.5)
FVC* ^a	87.5 (9.1)	92.2 (8.0)	102.2 (23.6)	111.1 (14.9)
FEV_1 * ^a	79.2 (9.1)	87.0 (8.7)	92.3 (19.3)	108.1 (13.8)
FRC ^a	97.2 (19.9)	98.1 (12.5)	128.1 (21.4)	125.0 (23.8)
TLC ^a	93.2 (8.3)	93.7 (7.5)	109.7 (11.8)	110.9 (14.8)
RV ^a	106.6 (31.3)	95.2 (18.7)	113.4 (39.4)	102.6 (33.7)

Except for ratios, figures are group mean (SD).

*Statistically significant differences between preterms and term born controls.

^aLung function data are given as group mean of two replicate tests and expressed as percentages of the predicted values. Lung volumes are represented by the panting technique.

V_{tg} was estimated by applying the mathematical algorithms installed by the manufacturer. Subsequently, the mean V_{tg} was calculated. Pressure-volume loops were considered technically inadequate if the pressure gradient exceeded 1.5 kPa or if there were obvious 'looping' or open ends, nonlinear segments or other major irregularities. Cursor lines for slope calculations were adjusted only if obvious artefacts in the pressure-volume loops were present (Lord & Brooks, 1977; Sauder, 1982).

With the single inspiratory effort technique, the breathing frequency was about 20 min⁻¹. The shutter closed at the end of a tidal expiration and data collection was triggered to start at an inspiratory mouth pressure of 0.25 kPa. The shutter was released when the pressure had increased by another 0.25 kPa, and calculation of V_{tg} was based on pressure-volume plots recorded in the interval between 0.25 and 0.50 kPa. The sampling rate was 125 Hz.

With both techniques V_{tg} was adjusted to obtain FRC. TLC was calculated by adding inspiratory capacity (IC) to FRC, and RV by subtracting the expiratory vital capacity (VC) from TLC (Quanjer et al., 1993). At least three test-manoeuvres were performed and each final test-report was based on their average. The same experienced technician performed all tests, blinded to results obtained in any previous test sessions.

Statistical methods

The repeatability (precision) of each technique was determined by calculating the standard deviations (SD) of the differences between the two replicate measurements. Agreement between the two techniques was assessed by calculating the SDs of the differences between the paired measurements obtained with the two techniques. The SDs were used to calculate 95% limits of agreement (Bland & Altman, 1986, 1999) between replicate measurements obtained with the same technique as well as 95% limits of agreement between the two techniques. Results are expressed in litres as well as in percentages of the average of paired measurements. Repeatability of the techniques and the agreement between them were visualized by plotting the differences between paired measurements of FRC against the average values of the measurements. Concordance between paired measurements was visualized by means of Kaplan–Meier plots (Luiz et al., 2003). To assess if variability increased with increasing magnitude of the measurements, the absolute values of the differences between paired measurements (log₁₀ transformed) were regressed on the average values of the measurements. Comparisons between independent groups were assessed with Student's *t*-test and Levene's test for equality of the variances. SPSS version 11.0 was used for computations. The level of significance was 0.05.

Results

Repeatability of the methods

Sixty-nine of the 70 10-year-old children successfully completed the four body plethysmography tests. In the control group, the

two subjects defined as asthmatics were excluded from the analysis whereas the preterm group was analysed with and without its 10 asthmatics included. The differences between the mean values of replicate measurements obtained with the same technique were small and <0.08 l for all variables, but deviated significantly from zero for some.

In healthy non-asthmatic control subjects, the SDs of the differences between replicate measurements varied from 0.13 to 0.16 l with the panting technique and from 0.18 and 0.23 l with the single inspiratory effort technique (Table 2). Neither asthma status nor gender influenced variance significantly. When comparing preterms with control subjects, variance was significantly higher only for RV measured with the panting technique ($P = 0.027$).

Figure 1 visualizes the repeatability of FRC, depicting individual differences between replicate tests against their average. As can be observed for FRC, variability did not increase with increased magnitude of any of the measured lung volumes.

Figure 2 portrays discordance between individual replicate measurements of FRC for each technique. The differences exceeded 0.4 l for about 5% of test-pairs with both methods. The proportion with a discordance of more than 0.18 l (approximately 1 SD) was however, approximately 0.25 with the panting technique compared with 0.45 with the single inspiratory effort technique.

Table 2 Repeatability of the panting and single inspiratory effort technique in 10-year-old children.

	Panting		Single inspiratory effort	
	1 SD ^a	95% limits of agreement ^b	1 SD ^a	95% limits of agreement ^b
FRC				
Non-asthmatic controls	0.16	20.3	0.18	23.1
Non-asthmatic preterms	0.17	23.8	0.18	26.3
All preterms	0.18	23.3	0.19	28.8
TLC				
Non-asthmatic controls	0.13	8.0	0.18	11.5
Non-asthmatic preterms	0.19	12.9	0.18	12.2
All preterms	0.21	12.5	0.18	12.4
RV				
Non-asthmatic controls	0.14	39.5	0.23	66.7
Non-asthmatic preterms	0.20	60.0	0.23	72.2
All preterms	0.22	59.9	0.22	72.3

^a1 SD (litres) of the differences between the two replicate measurements of the same lung volume, measured with the respective techniques.

^b1.96 SDs of the differences between the two replicate measurements, reported as percentage of the mean values of the two measurements. Data are given for the non-asthmatic controls ($n = 33$), for non-asthmatic preterms ($n = 25$) and for all preterm ($n = 34$).

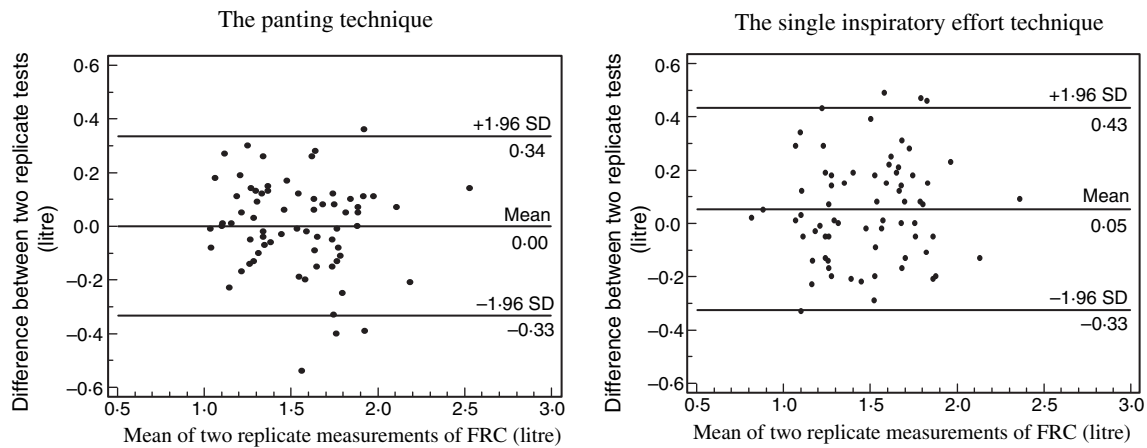


Figure 1 Repeatability of FRC in 10-year-old children. Each point represents the difference between two replicate measurements obtained with the same technique in the same individual, plotted against the average value of the test-pairs. Horizontal lines represent ± 1.96 SD of the differences in litres. All the 69 tested 10-year-old subjects are included.

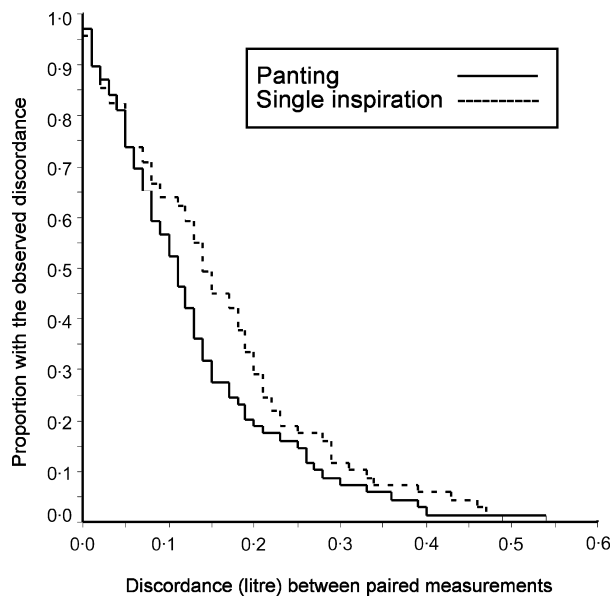


Figure 2 Discordance between replicate measurements of FRC obtained with the panting and the single inspiratory effort technique in 10-year-old children. The x-axis represents the absolute difference between replicate measurements, and the y-axis represents the proportion of pairs with at least the observed difference. All the 69 tested 10-year-old subjects are included.

A negative correlation was observed between FRC and IC regarding differences between repeated measurements (Pearson's correlation coefficient, -0.421 with the panting and -0.522 with the single inspiratory effort technique, $P < 0.001$ for both estimates).

Agreement between the methods

Of all the included 162 subjects, 155 completed at least one set of panting and single inspiratory effort manoeuvres. The seven

failures were among the preterm adolescents. The mean differences between paired measurements with the two techniques were 0.04 , 0.03 and 0.04 l for FRC, TLC and RV, respectively, not significantly different from zero. The variance of the differences between paired measurements did not differ significantly between the genders or between preterm and control subjects and was not significantly influenced by asthma status (Table 3). The SDs of the differences for FRC, TLC and RV were all in the same range and between 0.26 and 0.28 l in non-asthmatic control subjects and between 0.30 and 0.32 l in non-asthmatic preterms (Table 3). Variability increased with increasing magnitude of the measurements, visualized for FRC in Fig. 3 ($P < 0.001$, $P = 0.004$ and $P < 0.001$ for FRC, TLC and RV, respectively). In litres, the extent of discordance between the panting and single inspiratory effort method was shown to be similar for FRC, TLC and RV (Fig. 4).

Discussion

This study has confirmed that children at the age of 10 are capable of performing whole body plethysmography. The panting and the single inspiratory effort technique produced results that were comparable in magnitude over a wide range of lung volumes, however with a better precision with the panting technique. The variability of Vtg and FRC and not the variability of IC and VC accounted for most of the variability of TLC and RV.

As high pressure gradients against the occluding shutter may introduce small errors with the single inspiratory effort technique (Coates et al., 1997), Vtg was determined within a narrow pressure window. A high sampling frequency allowed for an ample number of sample points. The dead space added by the filter and the mouthpiece was included in the applied algorithms and dealt with by the software. Dead space volume was kept as low as possible as a different temperature response to pressure changes may have some influence on the measurements.

	Non-asthmatic controls (n = 74)		Non-asthmatic preterms (n = 55)		All preterms (n = 74)	
	1 SD ^a	95% limits of agreement ^b	1 SD ^a	95% limits of agreement ^b	1 SD ^a	95% limits of agreement ^b
FRC	0.26	21.1	0.30	24.5	0.29	24.6
TLC	0.26	11.0	0.32	14.0	0.31	14.1
RV	0.28	58.2	0.32	63.3	0.31	61.1

Table 3 Agreement between the panting and the single inspiratory effort technique.

^a1 SD (litres) of the differences between paired measurements of the same lung volume, measured with the panting and the single inspiratory effort technique.

^b1.96 SDs of the differences between the paired measurements, reported as percentage of the mean values of the two measurements.

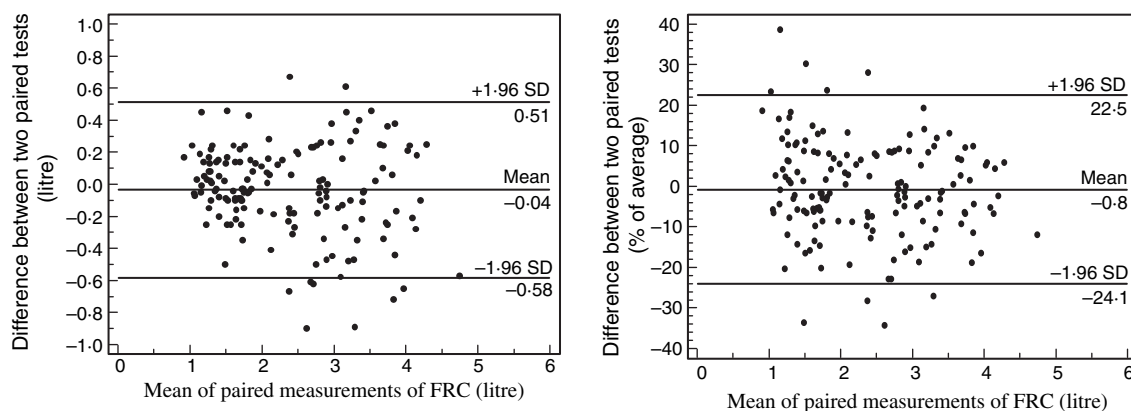


Figure 3 Comparison of the two methods. Each point represents the difference between paired measurements of FRC obtained with the panting and the single inspiratory effort technique in the same individual, plotted against the average value of the test pair. Horizontal lines represent ± 1.96 SD of the differences in litres (left side) and ± 1.96 SD of the differences in percentage of their average values (right side). All the 155 tested subjects are included.

As bronchial hyperreactivity could be expected to influence variability, asthmatics were excluded from the control population. Half the study population were preterms with a potential for a wide range of disorders (Eber & Zach, 2001). Despite somewhat inferior repeatability, they did not perform principally different from healthy controls.

Repeatability

There was no obvious explanation for the deviation from zero that was observed for some differences between mean values of replicate measurements. The panting technique had better repeatability than the single inspiratory effort technique (Table 2). With the panting technique, Vtg is determined from the average of a number of pressure volume loops consisting of a compression as well as a rarefaction phase. With the single inspiratory effort technique, calculations are based on one single unidirectional slope, a fact that may contribute to its reduced precision. Figure 2 illustrates that the fraction of replicate measurements with discordance in the medium range was smaller with the panting than the single inspiratory effort technique whereas the fraction with a high discordance was comparable for both methods. The likelihood of making large mistakes therefore seems to be similar with both techniques.

In this 10-year-old population, the size of the measurements did not predict variabilities (Fig. 1). Thus, the expression of variability as percentages of the measured volumes may overestimate variability in the low range and underestimate variability in the high range of the measurement values.

The negative correlation observed between the differences in IC and FRC indicates that a significant proportion of the variability of IC can be explained by the variability in FRC. When IC was subsequently added to FRC to obtain TLC, the variability of TLC reflected the variability of FRC. Measurements of Vtg and FRC and not variability in IC and VC manoeuvres thus accounted for most of the variability in TLC and RV.

Method comparison

Comparing the magnitude of the measurements obtained with the panting and the single inspiratory effort techniques, no systematic differences were demonstrated (Fig. 3). For all variables assessed, the differences between the methods were clinically negligible and not significantly different from zero. This contrasts a previous report, where significantly higher values were observed if Vtg was obtained with the single inspiratory effort technique (Desmond et al., 1988). In healthy control subjects, 1 SD of the differences between paired measurements obtained with the two techniques

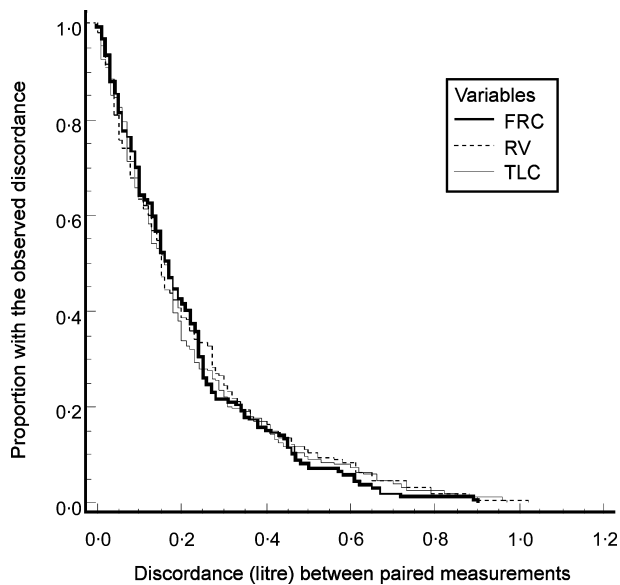


Figure 4 Discordance between paired measurements obtained with the panting and single inspiratory effort technique. Absolute differences between measurements obtained with the two techniques are depicted in litres on the x-axis, and the proportion of pairs with at least the observed difference on the y-axis. All the 155 tested subjects are included.

was in the range of 0.26–0.28 l (Table 3) and the extent of discordance between methods was similar for all lung volumes (Fig. 4). Variabilities increased with increasing mean values of paired measurements, justifying the expression of variability as percentages of the magnitude of the measurements.

Recent data on precision of lung volume measurements in children is insufficient and the literature comparing the different measurement methods is scarce. A coefficient of variation of about 5% for Vtg measured at FRC (DuBois et al., 1955; Quanjer et al., 1971) was suggested in a recent review (Quanjer et al., 1993), translating to 95% limits of agreement of approximately 10%. In 20 healthy children examined repeatedly with the panting technique (Hutchison et al., 1981), TLC, RV and FRC had similar absolute variabilities in the range of 100–300 ml, and the precision observed was comparable to ours. In contrast to our study however, they reported a significant correlation between the variability and the magnitude of the measurements. In a more recent study (Walamies, 1998), a coefficient of variation for FRC and RV of respectively 9 and 24% was reported for the panting technique, a precision that is comparable to ours.

Conclusions

Ten-year-old children are capable of performing plethysmography with the panting as well as the single inspiratory effort technique. No systematic differences were observed between the two techniques. Despite a lower precision, the single inspiratory effort technique can be used as an alternative method to assess lung volumes if the standard panting technique fails.

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