



Lung ultrasound features and relationships with respiratory mechanics of evolving BPD in preterm rabbits and human neonates

This is the peer reviewed version of the following article:

Original:

Loi, B., Casiraghi, C., Catozzi, C., Storti, M., Lucattelli, M., Bartalesi, B., et al. (2021). Lung ultrasound features and relationships with respiratory mechanics of evolving BPD in preterm rabbits and human neonates. JOURNAL OF APPLIED PHYSIOLOGY, 131(3), 895-904 [10.1152/jappphysiol.00300.2021].

Availability:

This version is available <http://hdl.handle.net/11365/1232439> since 2023-05-19T08:44:57Z

Published:

DOI:10.1152/jappphysiol.00300.2021

Terms of use:

Open Access

The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. Works made available under a Creative Commons license can be used according to the terms and conditions of said license.

For all terms of use and more information see the publisher's website.

(Article begins on next page)

1
2
3 **Lung ultrasound features and relationships with respiratory**
4 **mechanics of evolving BPD in preterm rabbits and human**
5 **neonates**
6

7 Barbara Loi (MD),^{1*} Costanza Casiraghi (PhD),² Chiara Catozzi (MSc),²
8 Matteo Storti (MSc),³ Monica Lucattelli (MD),⁴ Barbara Bartalesi (MD),⁴
9 Nadya Yousef (MD, MSc),¹ Fabrizio Salomone (PhD)²
10 and Daniele De Luca (MD, PhD)^{1,5*}

11
12 *1 Division of Pediatrics and Neonatal Critical Care, "A.Béclère" Medical Centre, Paris*
13 *Saclay University Hospitals, APHP (Paris – France)*
14

15 *2 Neonatology and Pulmonary Rare Disease Unit. Pharmacology & Toxicology Dept.*
16 *Corporate Preclinical R&D, Chiesi (Parma – Italy)*
17

18 *3 Department of Chemical & Life Sciences and Environmental Sustainability, University of*
19 *Parma (Parma – Italy)*
20

21 *4 Department of Molecular and Developmental Medicine, University of Siena (Siena – Italy)*
22

23 *5 Physiopathology and Therapeutic Innovation Unit-INSERM U999, Paris Saclay University*
24 *(Paris – France)*

25 **Running title:** Preterm rabbits share lung ultrasound appearance with infants with evolving
26 BPD

27 **Running head:** Preterm rabbits resemble lung ultrasound features of human BPD

28
29 **Word count:** 3237
30

31 **Corresponding authors:**

32 ***Daniele De Luca MD, PhD**

33 Service de Pédiatrie et Réanimation Néonatale

34 Hôpital "A. Béclère", GHU Paris Saclay, APHP

35 157 rue de la Porte de Trivaux, 92140 Clamart (France)

36 Tel: +33 (0)145374837 - Fax: +33 (0)145374546 - Email: dm.deluca@icloud.com

37 ***Barbara Loi MD**

38 Email: barbara.loi@aphp.fr
39

40 **ABSTRACT** - Evolving bronchopulmonary dysplasia (BPD) is characterized by impaired
41 alveolarization leading to lung aeration inhomogeneities. Hyperoxia-exposed preterm rabbits
42 have been proposed to mimic evolving BPD; therefore, we aimed to verify if this model has the
43 same lung ultrasound and mechanical features of evolving BPD in human neonates. Semi-
44 quantitative lung ultrasound and lung mechanics measurement were performed in twenty-five
45 preterm rabbits (28 days of gestation) and twenty-five neonates (mean gestational age \approx 26 weeks)
46 with evolving BPD. A modified rabbit lung ultrasound score (rLUS) and a validated neonatal lung
47 ultrasound score (LUS) were used. Lung ultrasound images were recorded and evaluated by two
48 independent observers blinded to each other's evaluation. Lung ultrasound findings were equally
49 heterogeneous both in rabbits as in human neonates and encompassed all the classical lung
50 ultrasound semiology. Lung ultrasound and histology examination were also performed in 13 term
51 rabbits kept under normoxia as further control and showed the absence of ultrasound and histology
52 abnormalities compared to hyperoxia-exposed preterm rabbits. The inter-rater absolute agreement for
53 the evaluation of lung ultrasound images in rabbits was very high (ICC: 0.989 (95%CI: 0.975-0.995);
54 $p < 0.0001$), and there was no difference between the two observers. Lung mechanics parameters were
55 similarly altered both in rabbits and human neonates. There were moderately significant correlations
56 between airway resistances and lung ultrasound scores in rabbits ($\rho = 0.519$; $p = 0.008$) and in neonates
57 ($\rho = 0.409$; $p = 0.042$). In conclusion, the preterm rabbit model fairly reproduces the lung ultrasound
58 and mechanical characteristics of preterm neonates with evolving BPD.

59 **NEW AND NOTHEWHORTY**

60 We have reported that hyperoxia-exposed preterm rabbits and human preterm neonates with
61 evolving BPD are the same lung ultrasound appearance, and that lung ultrasound can be
62 fruitfully applied on this model with a brief training. The animal model and human neonates
63 also presented the same relationship between semiquantitative ultrasound-assessed lung aeration
64 and airway resistances. In conclusion, this animal model fairly reproduce evolving BPD as it is
65 seen in clinical practice.

66 INTRODUCTION

67 Bronchopulmonary dysplasia (BPD) is characterized by an impaired lung development due to the
68 aberrant reparative response to both pre- and post-natal lung injury.(1) From a parenchymal
69 perspective, developing BPD is an evolutive and regionally heterogeneous disorder characterized by
70 impaired alveolarization leading to structural lung tissue modifications and lung aeration
71 inhomogeneities.(1) Given its multifactorial nature, mimicking BPD in animal models remains a
72 challenging task. Ideally, an animal model of BPD should include a preterm birth and some possible
73 lung injury triggers, such as invasive ventilation, inflammation or oxidative stress. Additionally,
74 animal care should be as similar as possible to that provided in neonatal intensive care units
75 (NICU).(2) Moreover, animals should be supported for long periods, since the chronic respiratory
76 disease of preterm infants cannot be resumed in a punctual diagnosis at a given time point. In fact,
77 preterm infants are rather affected by a chronic respiratory failure representing a *continuum* evolving
78 over time from early life to infancy and characterized by persistent airway and pulmonary vascular
79 disease: this is expressed by the “chronic pulmonary insufficiency of prematurity” concept.(3)
80 For instance, lambs, pigs, baboons or monkeys are effective to mimic the clinical reality in detail,
81 albeit they may be less cost-effective compared with small laboratory animals.(4, 5) Newborn rodents
82 can be delivered at term during the saccular stage of lung development, which is morphologically
83 similar to the human premature.(6) Nonetheless, these animals are difficult to ventilate and lack the
84 significant impact of preterm birth. Therefore, they cannot reproduce the complex reality of neonatal
85 critical care and the translatability of this model to human BPD can be questioned. Large animals and
86 rodents also have different survival, with the former surviving for longer times, which impacts the
87 type of studies that can be performed and their costs. Rabbits represent an excellent compromise to
88 model BPD since they have many offspring, can be delivered prematurely and allow some perinatal
89 manipulations, making the model closer to the actual neonatal care.(2, 7) For instance, preterm
90 rabbits are fed artificially with milk formula and can be exposed to hyperoxia to induce the
91 alveolarization arrest similar to what occurs in infants with evolving BPD.(8, 9)

92

93 From the imaging point of view, the heterogeneous parenchymal abnormalities of BPD can be
94 accurately described by lung ultrasound, which is characterized by a steady loss of lung aeration over
95 time.(10) By this means, early lung ultrasound performed at 7-14 days of post-natal age can predict
96 the occurrence of BPD at 36 weeks post-menstrual age.(10) From a mechanical point of view, BPD is
97 characterized by a mixed pattern (obstructive and restrictive) with heterogeneous distribution and a
98 certain variability according to clinical severity.(11) The lung ultrasound features of hyperoxia-
99 exposed preterm rabbits are unknown. Therefore, the present study compared the lung ultrasound and
100 mechanical features of preterm rabbits and human neonates with evolving BPD to validate the
101 hyperoxia-exposed preterm rabbit as a reliable model of BPD.

102

103 **MATERIALS AND METHODS**

104

105 This project was divided into two phases: 1) an experimental model of evolving BPD in hyperoxia-
106 exposed preterm rabbits, and 2) data collection in extremely preterm infants with evolving BPD.

107 *Experimental model and animal care*

108 Time-mated New Zealand White female rabbits were purchased from Charles River Laboratories
109 (Miserey, France). Pregnancy was confirmed with ultrasounds at 12-14 days after the artificial
110 insemination. Subsequently, they were maintained with *ad libitum* food and water until caesarean
111 section was performed. At 28 days of gestation, which is equivalent to the sacular stage of human
112 lung development,(2, 7) does (3.7 ± 0.4 kg of body weight) were sedated with medetomidine 2 mg/kg
113 (Domitor[®], Orion, Espoo, Finland). Ten minutes later, the animals received 25 mg/kg of ketamine
114 (Imalgene 1000[®], Merial, France) and 5 mg/kg of xylazine (Rompun[®], Bayer, Leverkusen,
115 Germany). When adequate sedation was reached, the abdomen was shaved and does were euthanized
116 with pentothal sodium (50 mg/kg; MSD Animal Health, Madison-NJ, USA). All drugs were given
117 intramuscularly. The abdomen was immediately opened through a low midline abdominal incision,
118 the uterus was exposed, and pups were extracted. They were dried, stimulated and placed in the

119 incubator at 32°C, with 95% oxygen and 50-60% relative humidity. After 1h, the surviving pups
120 were weighed, numbered and placed on soft bedding for 7 days with no treatment. Housing material
121 was changed daily. Pups were fed twice a day through 3.5 Fr esophageal tubes (Vygon, Ecoen,
122 France) transiently introduced for the feeding which lasted few minutes. A milk replacer (Day One[®],
123 Protein 30%, Fat 50%; FoxValley, Aurora-IL, USA) dissolved in water (250 mg/mL) was given. The
124 volume of each feed was increased from 40 mL/kg/day on the day of birth, to 50 mL/kg/day on day
125 1, 75 mL/kg/day on day 2, and 100 mL/kg/day from day 3 to day 7. Pups were stimulated twice daily
126 to urinate before feeding. A mixture of pre- (fructo-oligosaccharide and acacia) and pro-biotics
127 (*Saccharomyces cerevisiae*) were added for all 7 days (Bio-Lapis[®]; Probiotics International, UK; 25
128 mg/mL), whereas immunoglobulins (15 mg/mL) were added only for the first 3 days (Col-o-Cat[®],
129 SanoBest, Hertogenbosch, Netherlands). On day 2, vitamin K was intramuscularly given (0.25
130 mg/kg, Izokappa[®], Brescia, Italy). These rabbits generally open eyelids around 7-10 days of life,
131 which is similar to what happens in extremely preterm human neonates.(12, 13)

132 A control group of newborn rabbits without lung injury was also included. This consisted of term
133 rabbits naturally delivered on the 31st day of gestation, which is their physiological term of pregnancy
134 and correspond to human lung development's alveolar stage .(12) After birth, pups were maintained
135 with their mothers at room air in individual cages until day 4 in order to reach the age equivalence
136 with preterm pups at day 7. At the end of all experiments, newborn rabbits were euthanatized as
137 described above. The protocol was approved by the Italian Ministry of Health review board
138 (n°744/2017) and met all the local and European regulations on animal research. This study phase
139 followed ARRIVE guidelines.(14)

140 *Semi-quantitative lung ultrasound in rabbits*

141 On days 7 and 4 in preterm and term rabbits, respectively, the animals were anesthetized with
142 isoflurane (3% in pure oxygen). The lung ultrasound procedure in adult rabbits has been already
143 described.(15) Here, we adapted the technique to apply it to newborn rabbits and particularly to
144 preterm rabbits. Each lung was scanned using a hand-held ultrasound tablet equipped with a “hockey

145 stick” and a micro-linear, high-resolution probe (18 MHz, 2.5 cm length, Sonoscanner U-LITE[®]
146 EXP, Sonoscanner, Paris, France). Since the probe was relatively large compared to the rabbit chest,
147 the evaluation was done on the whole hemithorax (i.e. without division in smaller chest areas) as
148 performed by Raimondi et al. in neonates scanned with a broadband linear probe.(16) A simplified
149 rabbit lung ultrasound score (rLUS) was adapted from the previously validated neonatal lung
150 ultrasound score (LUS).(17) rLUS and LUS were based on the same lung ultrasound semiology, and
151 all images were evaluated according to the classical lung ultrasound scoring system assigning 0-to-3
152 points.(17, 18) If the rabbit lung appeared homogenous, a single picture (300 dpi) per lung was
153 captured (one picture for the left and one for the right lung); if the lung appearance was not
154 homogenous, additional pictures were recorded to capture all ultrasound features, which were
155 averaged for each rabbit. Ultrasound scans were performed both transversally and longitudinally,
156 with automatic gain adjustment, using the dedicated software feature of the ultrasound device; no
157 harmonics were used. Depth and focus were adjusted according to chest size and the sign of
158 interest.(19) Illustrative pictures of lung ultrasound procedure and findings, as well as rLUS
159 calculation, are shown in **Fig.1**. All images per each rabbit were independently evaluated by the
160 investigator (CCas) performing the ultrasound and animal care, who received a short formal lung
161 ultrasound training, as described elsewhere (20), and by a skilled neonatologist with several years of
162 lung ultrasound experience (DDL), who did not participate in animal care and performed the
163 evaluation blinded to any animal data.

164 *Lung mechanics in preterm rabbits*

165 Preterm rabbits also underwent pulmonary function tests immediately after lung ultrasound.
166 Pulmonary function was studied with the forced oscillation technique, using the FlexiVentTM system
167 equipped with module 2 (Scireq, Montreal, Canada), as we previously described.(21) A tracheostomy
168 was performed and an 18-gauge needle was inserted in the trachea and tied. Pups were connected to
169 the FlexiVent ventilator (tidal volume: 10 mL/kg, frequency: 120 breaths/min, positive end-
170 expiratory pressure (PEEP): 3 cmH₂O).(21) In addition to total inspiratory capacity, airway resistance

171 (Raw), dynamic compliance (C_{dyn}), lung tissue damping and elastance were measured using the
172 Prime-8 and Snapshot-120 perturbation programs, respectively, as previously described.(22) All
173 measurements were performed until three consistent values (with a minimum $R^2 > 0.95$) were obtained
174 and averaged.

175 **Histology**

176 Right after the sacrifice, the trachea was cannulated with a 20-gauge catheter. Lungs were removed
177 and fixed with 10% buffered formalin (Sigma-Aldrich, St.Louis-MI, USA) for at least 4 hours under
178 constant pressure (25 cmH₂O) using a custom-made fixation device to ensure homogenous fixation
179 pressures. Subsequently, the lungs were first left in formalin for at least 24h, then transferred to 70%
180 ethanol, embedded in paraffin, and stained with eosin and hematoxylin (H&E) following standard
181 histology protocols. A section for each lung was used to evaluate the mean linear intercept (Lm).(23)
182 Lm was evaluated in 40 fields per section to cover the entire section area by calculating the number
183 of intersections between the reference line and the alveolar tissue using a micrometric scale; Lm
184 value of the right and left lung were then averaged and used in the analysis.(24, 25)

185 **Patients**

186 Neonates were enrolled between 2018 and 2020 in a prospective cohort study performed in an
187 academic tertiary referral NICU if they fulfil all the following criteria: 1) gestational age
188 $\leq 28^{+6}$ weeks; 2) invasive ventilation and oxygen supplementation at 14th day of postnatal life for
189 ongoing hypoxemic respiratory failure; 3) invasive ventilation for at least 10 days in the first 2 weeks
190 of life. Exclusion criteria were: 1) severe hemodynamic instability (defined as any need for
191 inotropes); 2) need for surgery; 3) air leaks; 4) grade III-IV intraventricular hemorrhage; 5)
192 congenital lung anomalies; 6) major congenital malformations or chromosomal abnormalities. In
193 addition, all enrolled neonates had to qualify for BPD diagnosis at 36 weeks post-menstrual age
194 according to the National Institute for Child Health and Development criteria(26) otherwise, they
195 would have been excluded *a posteriori*. Data were collected in real-time by attending physicians in
196 charge of patients, and no procedure was performed solely for the study participation. In fact, lung

197 ultrasound and mechanics evaluation are part of our routine care and are serially performed in long-
198 term ventilated neonates with evolving BPD.(10, 27) Data were anonymously collected in a
199 dedicated and secured database, respecting all local and European privacy regulations. The protocol
200 was approved by the local ethical committee (SRLF16/58), and written informed consent was
201 obtained from parents/guardians upon NICU admission. This study phase followed STROBE
202 guidelines.(28)

203 *Semi-quantitative lung ultrasound in preterm neonates*

204 We performed lung ultrasound on the 14th day of postnatal life (while all neonates were invasively
205 ventilated) as lung ultrasound score peaks and has the highest diagnostic accuracy to predict BPD at
206 this time-point.(10) We calculated the classical neonatal LUS on 6 chest areas (3 per each side),
207 assigning 0-to-3 points to each area (total score going from 0 to 18), based on lung ultrasound
208 semiology patterns, as previously described.(17) Transversal and longitudinal scans were performed
209 on all chest areas with a “hockey stick”, micro-linear, high-resolution probe (15 MHz; CX-50 Philips
210 Healthcare, Eindhoven, The Netherlands), as previously reported.(18) Exams were accomplished in a
211 standardized manner when ventilation was optimized and infants were in a calm state, using the same
212 technical settings described above for rabbits. No sedation was needed to perform lung ultrasound.
213 Clinicians performing ultrasound had at least 1 year of experience in daily use of lung
214 ultrasound,(19) as this is the first-line imaging technique in our NICU.(27)

215 *Lung mechanics in preterm neonates*

216 Neonates were intubated with appropriately sized endotracheal tubes, lightly sedated as previously
217 described.(29) Time-cycled, pressure-regulated, assisted-controlled ventilation was provided with the
218 following targets: 5-6 ml/kg tidal volume, 7.4 pH, and 35-65 mmHg PaCO₂. PEEP was set between 5
219 and 8 cmH₂O. A maximal peak pressure of 22 cmH₂O was allowed, FiO₂ was as low as possible to
220 guarantee a peripheral hemoglobin saturation between 90% and 95% and PaO₂ between 50 and 70
221 mmHg. The flow trigger was set at the maximal possible sensitivity without auto-triggering.
222 Inspiratory time and flow were set looking at flow and pressure tracings and aiming to avoid any gas-

223 trapping and optimize synchrony. All patients were on continuous flow neonatal ventilators equipped
224 with a low dead-space, hot-wire anemometers. Airway pressure and flow were both measured at the
225 Y-piece (30) to maximize the accuracy of lung mechanics assessment. Ventilators were subjected to
226 serial technical quality controls.(31) Sensors were calibrated before each use and manufacturers'
227 recommendations were always followed. Lung mechanics was evaluated within 1h from lung
228 ultrasound, considering Raw and Cdyn shown by a breath-to-breath analysis on the ventilator screen.
229 Measurements were performed when neonates were stable, after airway suctioning, and following the
230 previously described technique.(32) In detail, spontaneous breathing was temporally avoided by
231 increasing mechanical rate, while the flow was decreased to 5L/min to reach a quasi-static situation.
232 In these conditions, when we observed gas leaks to be <5% and normal-appearing pressure-volume
233 and flow-volume loops, Raw and Cdyn were averaged on 10 mechanical breaths showing identical
234 tracing.

235 *Statistics*

236 We enrolled 25 preterm rabbits as in previous studies describing lung mechanics and pathology of
237 this experimental model.(33) To be consistent, we aimed to enroll the same number of neonates with
238 evolving BPD in the second study phase. We also enrolled 13 term rabbits as further controls. Data
239 were tested for normality with the Shapiro-Wilk test and expressed as mean (standard deviation) or
240 median [interquartile range], as appropriate. Data sets were compared with Student or Mann-Whitney
241 test, respectively. The conformity of lung ultrasound interpretation, that is, the inter-rater absolute
242 agreement between the two independent observers, was evaluated using the intra-class correlation
243 coefficient (ICC).(34) rLUS and LUS were correlated with lung mechanics measures in preterm
244 rabbits and neonates, respectively, using Spearman correlation coefficient (ρ). Results were also
245 graphically shown using scatter plots analyzed with local (smoother) regression with 95%
246 Epanechnikov kernel; $p < 0.05$ values were considered statistically significant. Analyses were
247 performed using SPSS version 27.

248

249 RESULTS

250

251 Details of preterm rabbits and human neonates recruited in the first and second project phase are
252 summarized in **Tab.1**. All enrolled neonates were invasively ventilated at the fourteenth day of life
253 with a mean airway pressure of 15 (1.8) cmH₂O. They were ventilated for ongoing respiratory failure
254 due to evolving BPD, and no infant had other concomitant reasons to need invasive ventilation: the
255 total duration of invasive ventilation was 13 [11-16] days. During their NICU stay, 6 (24%) neonates
256 needed postnatal steroids to facilitate extubation, and 17 (68%) were treated at least once with
257 nebulized salbutamol for spells due to bronchospasm. All neonates qualified for BPD diagnosis at 36
258 weeks' gestation and were eventually discharged from the NICU: eight (32%) infants had mild, eight
259 (32%) had moderate, and nine (36%) had severe BPD. **Tab.2** shows lung mechanics variables: Raw
260 and Cdyn were respectively above and below the normal values, both in preterm rabbits and
261 neonates.

262

263 Lung ultrasound findings were heterogeneous in hyperoxia-exposed preterm rabbits and
264 encompassed normally aerated zones, zones with interstitial-alveolar pattern and others with total
265 loss of aeration. More than one picture per lung was recorded in 17 (68%) preterm rabbits (an
266 average of 2.9 (0.8) lung ultrasound images were taken per rabbit), as the lung appearance was not
267 homogenous (**Fig.1-2**). The inter-rater absolute agreement for the evaluation of lung ultrasound
268 images in preterm rabbits (ICC: 0.989 [95%CI: 0.975-0.995]; $p<0.0001$) was very high, and there
269 was no difference when rLUS was calculated by the animal lab investigator (1.6 [0.9-2]) or the
270 independent expert rater (1.6 [1-2]; $p=0.462$; **Fig.2**). All preterm rabbits completed the experimental
271 protocol; lung ultrasound lasted 2-3 minutes per rabbit and no issue was noticed during the
272 procedure. Lung ultrasound findings were also heterogeneous in neonates with evolving BPD: **Fig.3**
273 shows the similarities between the main lung ultrasound abnormalities in hyperoxia-exposed preterm
274 rabbits and neonates with evolving BPD.

275

276 **Fig.4** shows the relationship between lung ultrasound scores and Raw or Cdyn in preterm rabbits and
277 neonates. Raw significantly correlated with rLUS ($\rho=0.519$, $p=0.008$, $R^2=0.20$) and LUS ($\rho=0.409$,
278 $p=0.042$, $R^2=0.29$) (**Fig.4, Panel A and C**). There was no significant correlation between rLUS and
279 any other mechanics parameter in rabbits (Cdyn: $\rho=0.067$, $p=0.750$; inspiratory capacity: $\rho=0.463$,
280 $p=0.259$; tissue damping: $\rho=0.327$, $p=0.190$; elastance: $\rho=0.067$, $p=0.750$), nor between LUS and
281 Cdyn ($\rho=0.205$, $p=0.325$) in neonates.

282

283 **Fig.5** reports the differences between hyperoxia-exposed preterm rabbits and control rabbits
284 delivered at term and treated in normoxia. Typical histological findings of experimental BPD were
285 observed in preterm rabbits with extensive inflammation and airspace simplification (**Fig.5A-D**).
286 This is confirmed by Lm, which was higher in hyperoxia-exposed preterm rabbits compared to term
287 animals (**Fig.5G**). Illustrative images show that the lungs of preterm rabbits were poorly aerated,
288 compared to control animals (**Fig.5E-F**), and this is confirmed by rLUS, which was always zero in
289 term rabbits and significantly higher than in hyperoxia-exposed preterm rabbits.

290

291 **DISCUSSION**

292 Our study adds novel findings to the knowledge about experimental BPD models: we show that the
293 hyperoxia-exposed preterm rabbit model has similar lung ultrasound features and relationships with
294 lung mechanics (that is, correlation between lung ultrasound scores and Raw, lack of correlation with
295 other parameters) of evolving BPD in human neonates.

296

297 To our knowledge, this is the first use of lung ultrasound in an experimental model of BPD. Evolving
298 BPD in neonates is characterized by a non-homogeneous pattern composed of consolidated, tissue-
299 like zones with significant loss of aeration, zones with a more or less severe interstitial-alveolar
300 pattern, and zones with a normal aeration (10, 35). These features were also found in rabbits with
301 experimental BPD. Interestingly, these ultrasound findings were coherent with those obtained by

302 micro-CT scan demonstrating altered lung aeration in preterm rabbits,(36) and this is fully consistent
303 with data showing a close correlation between lung ultrasound score and CT-measured lung
304 aeration.(37, 38) The similarity can be attributed to the shared pathophysiology, such as impaired
305 alveolarization and airway development typical of both human BPD and the experimental BPD-like
306 phenotype generated in the rabbit model.(39, 40) Of note, lung ultrasound appearance looks similar
307 in preterm rabbits and human neonates, while lung development is also known to be comparable (41)
308 and we can estimate to have a similar developmental stage in preterm rabbits and human neonates
309 studied at 7 and 14 days of postnatal age, respectively. (12, 13, 41)

310

311 Semi-quantitative ultrasound assessment of lung aeration has been successfully applied in small
312 preterm rabbits, with similar probes, frequencies and procedures used in preterm neonates,
313 confirming the reliability of our findings. Interestingly, relatively novice and experienced operators
314 achieved similar lung ultrasound scores, exactly as observed in NICU care when operators of
315 different degrees of expertise performed lung ultrasound.(19) These data expand those showing the
316 feasibility of lung ultrasound in adult rabbit models of acute respiratory distress syndrome (15) or in
317 preterm rabbits with primary surfactant deficiency at birth (42) and represent the first example of
318 ultrasound-assessed lung aeration in a model of chronic, evolutive lung injury with a mixed
319 obstructive/restrictive pattern.

320

321 Our findings also show consisting similarities in the relationship between ultrasound-assessed lung
322 aeration and mechanics. Lung ultrasound scores correlated with Raw both in preterm rabbits and
323 human neonates, while no other significant correlation was found with any other lung mechanics
324 parameter. Infants with BPD have variably decreased compliance and increased resistances, leading
325 to non-uniform ventilation and time-constant (43) and this inhomogeneity is well described by our
326 heterogeneous lung ultrasound findings. In addition, established BPD seems to be particularly
327 characterized by small airway obstruction, (44) and this may explain the observed relationship

328 between Raw and the lung ultrasound scores. When resistances are higher due to small airway
329 obstruction, lung parenchyma is less aerated, resulting in higher lung ultrasound scores. Small airway
330 obstruction may also explain the lack of correlation between lung ultrasound scores and Cdyn as
331 significantly obstructed lung zones are less ventilated and cannot contribute to the Cdyn calculation.
332 The lack of correlation between rLUS and other mechanical parameters in rabbits may be due either
333 to the non-homogeneous lung injury pattern and the relatively low resolution of lung ultrasound,
334 which cannot provide further details in these small animals. Correlation findings are analogous in the
335 experimental model and in neonates with evolving BPD, confirming the equally impaired lung
336 mechanics (33, 36) as results of similar histology abnormalities.(39, 40) In fact, all lung mechanics
337 parameters showed in **Tab.2** are significantly impaired compared to term rabbits with no lung
338 disease.(33) The analyses performed in term rabbits as further control corroborate our findings. In
339 fact, histology clearly shows typical features of lung injury mimicking BPD in hyperoxia-exposed
340 preterm,(33) while these were absent in term rabbits. Also, lung ultrasound findings were
341 heterogeneous in preterm rabbits as in human neonates with evolving BPD,(10) while lung
342 ultrasound appearance was always normal in term rabbits, exactly as it is always observed in term
343 neonates without any respiratory disorder.(45)

344

345 This study has some limitations. The rabbit model is suitable but obviously cannot reproduce all the
346 features of evolving BPD. The effect of invasive ventilation is not considered, since preterm rabbits
347 were spontaneously breathing while the neonates were intubated. Other injuries such as fetal
348 inflammation or infections, that may add to the complexity of BPD development, are also not
349 considered in this model. Moreover, rabbits are not exposed to prenatal steroids, while hyperoxia is
350 avoided in neonates as much as possible. Studying a cohort of infants with evolving BPD serves as
351 “control” of the experimental model, further to the control rabbits delivered at term and unexposed to
352 hyperoxia.(33) The studied sample size is relatively small but is represented by a well-described
353 experimental model and by a homogeneous population of infants with severe ongoing respiratory

354 failure due to evolving BPD. The choice of BPD definition and a given time-point to perform LUS
355 may be seen as limitations. However, we only used the classical BPD definition since recent analyses
356 performed using multiple definitions have yielded similar diagnostic accuracy for LUS to predict
357 BPD.(35) Also, we only performed LUS at 14 days of postnatal age, because LUS predictivity for
358 BPD is best, while rabbit and human lung development are quite similar at this time-points.(10, 12)
359 Lung ultrasound has been applied for the first time in this experimental model and its use could be
360 improved with experience or smaller probes with higher resolution, albeit using the same devices and
361 protocols as in neonatal lung ultrasound guaranteed a fair comparison of resulting images. The
362 application of a given mean airway pressure by invasive ventilation during lung mechanics
363 measurements in rabbits can provide a certain alveolar recruitment and improve the lung aeration
364 compared to spontaneous breathing: as lung ultrasound and mechanics measurements in rabbits are
365 performed during spontaneous breathing and invasive ventilation, respectively, this may have
366 partially influenced results. However, this is unavoidable to perform lung mechanics measurements
367 and ventilation has been applied with low positive end-expiratory pressure: therefore, its influence, if
368 any, should have been minimal. Our population consisted of BPD neonates who survived and
369 obviously those who died during the NICU hospitalization might have worse lung mechanics, which
370 might influence results. However, mortality directly due to BPD is uncommon in newborn
371 populations similar to ours (46) and we wanted to mimic the majority of patients with evolving BPD.
372

373 **CONCLUSIONS**

374 Lung ultrasound features are similar in the preterm rabbit model of experimental BPD and in human
375 neonates with evolving BPD. Lung ultrasound is easy to be used even in small animals and with short
376 training. We found an inverse correlation between airway resistance and ultrasound-assessed lung
377 aeration both in preterm rabbits and neonates. The preterm rabbit model fairly reproduces the lung
378 ultrasound and mechanical characteristics of preterm neonates with evolving BPD.

379

380 DISCLOSURE

381 DDL received research and educational grants from Chiesi Pharmaceuticals spa and ABBVIE inc. He
382 served as lecturer for, Chiesi Pharmaceuticals spa, ABBVIE inc and Getinge. Finally, has been a
383 member of advisory boards for Chiesi Pharmaceuticals spa, ABBVIE inc, Airway Therapeutics and a
384 consultant for OPHIREX inc. These companies produce surfactants or surfactant components but had
385 no role at all in this project.

386 NY received travel grants from Chiesi Pharmaceuticals spa. This company produce surfactants or
387 surfactant components but had no role at all in this project.

388 CCas, CC, MS and FS are employees of Chiesi Pharmaceuticals spa.

389

390 ABBREVIATION LIST

391 BPD: broncho-pulmonary dysplasia; Cdyn: dynamic compliance; CRIB-II: critical risk index for
392 babies; ICC: Intra-class correlation coefficient; LUS: neonatal lung ultrasound score; NICU: neonatal
393 intensive care units; PEEP: positive end-expiratory pressure; Raw: airway resistance; rLUS: rabbit
394 lung ultrasound score.

395

396 REFERENCES

397 1. **Thébaud B, Goss KN, Laughon M, Whitsett JA, Abman SH, Steinhorn RH, Aschner JL,**
398 **Davis PG, McGrath-Morrow SA, Soll RF, Jobe AH.** Bronchopulmonary dysplasia. *Nat Rev Dis*
399 *Primers* 5: 78, 2019. doi: 10.1038/s41572-019-0127-7.

400 2. **Salaets T, Gie A, Tack B, Deprest J, Toelen J.** Modelling Bronchopulmonary Dysplasia in
401 Animals: Arguments for the Preterm Rabbit Model. *Curr Pharm Des* 23: 5887–5901, 2018.
402 doi: 10.2174/1381612823666170926123550.

403

404

- 405 3. **Steinhorn R, Davis JM, Göpel W, Jobe A, Abman S, Laughon M, Bancalari E, Aschner J,**
406 **Ballard R, Greenough A, Storari L, Thomson M, Ariagno RL, Fabbri L, Turner MA.** Chronic
407 Pulmonary Insufficiency of Prematurity: Developing Optimal Endpoints for Drug Development. The
408 *J Pediatr* 191: 15-21.e1, 2017. doi: 10.1016/j.jpeds.2017.08.006.
- 409 4. **Albertine KH.** Utility of large-animal models of BPD: chronically ventilated preterm lambs.
410 *Am J Physiol Lung Cell Mol Physiol* 308: L983–L1001, 2015. doi: 10.1152/ajplung.00178.2014.
- 411 5. **Yoder BA, Coalson JJ.** Animal models of bronchopulmonary dysplasia. The preterm baboon
412 models. *Am J Physiol Lung Cell Mol Physiol* 307: L970–L977, 2014.
413 doi: 10.1152/ajplung.00171.2014.
- 414 6. **Remesal A, De Luca D, San Feliciano L, Isidoro-Garcia M, Minucci A, Pocino K, Casas J,**
415 **Fabrias G, Capoluongo ED, de la Cruz DL.** Effect of prenatal steroidal inhibition of sPLA2 in a rat
416 model of preterm lung. *Pulm Pharmacol Ther* 36: 31–36, 2016. doi: 10.1016/j.pupt.2015.12.001.
- 417 7. **D'Angio CT, Ryan RM.** Animal models of bronchopulmonary dysplasia. The preterm and term
418 rabbit models. *Am J Physiol Lung Cell Mol Physiol* 307: L959–L969, 2014.
419 doi: 10.1152/ajplung.00228.2014.
- 420 8. **Lorenzo AV.** The Preterm Rabbit: A Model for the Study of Acute and Chronic Effects of
421 Premature Birth. *Pediatr Res* 19: 201–205, 1985. doi: 10.1203/00006450-198502000-00011.
- 422 9. **Mascaretti RS, Mataloun MMGB, Dolhnikoff M, Rebello CM.** Lung morphometry, collagen
423 and elastin content: changes after hyperoxic exposure in preterm rabbits.
424 *Clinics (Sao Paulo)* 64: 1099-1104, 2009. doi: 10.1590/S1807-59322009001100010.
- 425 10. **Loi B, Vigo G, Baraldi E, Raimondi F, Carnielli VP, Mosca F, De Luca D,** On behalf
426 of the LUSTRE (Lung UltraSound To pReTerm nEonates) study group. Lung Ultrasound to Monitor
427 Extremely Preterm Infants and Predict BPD: Multicenter Longitudinal Cohort Study.
428 *Am J Respir Crit Care Med* 2020 Dec 22. doi: 10.1164/rccm.202008-3131OC

- 430 11. **Kalikkot Thekkeveedu R, Guaman MC, Shivanna B.** Bronchopulmonary dysplasia: A
431 review of pathogenesis and pathophysiology.
432 *Respir Med* 132: 170–177, 2017. doi: 10.1016/j.rmed.2017.10.014.
- 433 12. **Dutta S, Sengupta P.** Rabbits and men: relating their ages.
434 *J Basic Clin Physiol Pharmacol* 29: 427–435, 2018. doi: 10.1515/jbcpp-2018-0002.
- 435 13. **Duerksen KM, Barlow WE, Stasior OG.** Fused Eyelids in Premature Infants.
436 *Ophthalmic Plastic Reconstr Surg* 10: 234–240, 1994. doi: 10.1097/00002341-199412000-00002.
- 437 14. **Percie du Sert N, Hurst V, Ahluwalia A, Alam S, Avey MT, Baker M, Browne WJ,**
438 **Clark A, Cuthill IC, Dirnagl U, Emerson M, Garner P, Holgate ST, Howells DW, Karp NA,**
439 **Lazic SE, Lidster K, MacCallum CJ, Macleod M, Pearl EJ, Petersen OH, Rawle F, Reynolds P,**
440 **Rooney K, Sena ES, Silberberg SD, Steckler T, Würbel H.** The ARRIVE guidelines 2.0: Updated
441 guidelines for reporting animal research.
442 *PLoS Biol* 18: e3000410, 2020. doi: 10.1371/journal.pbio.3000410.
- 443 15. **Li D, Liu D, Long Y, Wang X.** Use of Lung Ultrasound to Assess the Efficacy of an
444 Alveolar Recruitment Maneuver in Rabbits With Acute Respiratory Distress Syndrome.
445 *J Ultrasound Med* 34: 2209–2215, 2015. 34: 2209–2215, 2015. doi: 10.7863/ultra.14.11051.
- 446 16. **Raimondi F, Migliaro F, Sodano A, Umbaldo A, Romano A, Vallone G, Capasso L.**
447 Can neonatal lung ultrasound monitor fluid clearance and predict the need of respiratory support?
448 *Crit Care* 16: R220, 2012. doi: 10.1186/cc11865.
- 449 17. **Brat R, Yousef N, Klifa R, Reynaud S, Shankar Aguilera S, De Luca D.** Lung
450 Ultrasonography Score to Evaluate Oxygenation and Surfactant Need in Neonates Treated With
451 Continuous Positive Airway Pressure.
452 *JAMA Pediatr* 169: e151797, 2015. doi: 10.1001/jamapediatrics.2015.1797.
- 453 18. **De Martino L, Yousef N, Ben-Ammar R, Raimondi F, Shankar-Aguilera S, De Luca**
454 **D.** Lung Ultrasound Score Predicts Surfactant Need in Extremely Preterm Neonates.
455 *Pediatrics* 142(3). pii: e20180463. doi: 10.1542/peds.2018-0463, [date unknown].

- 456 19. **Gomond-LeGoff C, Vivalda L, Foligno S, Loi B, Yousef N, De Luca D.** Effect of
457 different probes and expertise on the interpretation reliability of point-of-care lung ultrasound.
458 *Chest* 157: 924-931, 2020. doi: 10.1016/j.chest.2019.11.013.
- 459 20. **Mazmanyany P, Kerobyan V, Shankar-Aguilera S, Yousef N, De Luca D.** Introduction
460 of point-of-care neonatal lung ultrasound in a developing country.
461 *Eur J Pediatr* 179:1131-1137, 2020. doi: 10.1007/s00431-020-03603-w.
- 462 21. **Salaets T, Gie A, Jimenez J, Aertgeerts M, Gheysens O, Vande Velde G, Koole M,
463 Murgia X, Casiraghi C, Ricci F, Salomone F, Villetti G, Allegaert K, Deprest J, Toelen J.** Local
464 pulmonary drug delivery in the preterm rabbit: feasibility and efficacy of daily intratracheal
465 injections.
466 *Am J Physiol Lung Cell Mol Physiol* 316: L589–L597, 2019. doi: 10.1152/ajplung.00255.2018.
- 467 22. **Gie AG, Regin Y, Salaets T, Casiraghi C, Salomone F, Deprest J, Vanoirbeek J,
468 Toelen J.** Intratracheal budesonide/surfactant attenuates hyperoxia-induced lung injury in preterm
469 rabbits.
470 *Am J Physiol Lung Cell Mol Physiol* 319: L949–L956, 2020. doi: 10.1152/ajplung.00162.2020.
- 471 23. **Campbell H, Tomkeieff SI.** Calculation of the internal surface of a lung.
472 *Nature* 170: 116–117, 1952.
- 473 24. **Cardini S, Dalli J, Fineschi S, Perretti M, Lungarella G, Lucattelli M.** Genetic
474 Ablation of the Fpr1 Gene Confers Protection from Smoking-Induced Lung Emphysema in Mice. *Am*
475 *J Respir Cell Mol Biol* 47: 332–339, 2012. doi: 10.1165/rcmb.2012-0036OC.
- 476 25. **Fineschi S, De Cunto G, Facchinetti F, Civelli M, Imbimbo BP, Carnini C, Villetti G,
477 Lunghi B, Stochino S, Gibbons DL, Hayday A, Lungarella G, Cavarra E.** Receptor for Advanced
478 Glycation End Products Contributes to Postnatal Pulmonary Development and Adult Lung
479 Maintenance Program in Mice.
480 *Am J Respir Cell Mol Biol* 48: 164–171, 2013. doi: 10.1165/rcmb.2012-0111OC.
- 481

- 482 26. **Jobe AH, Bancalari E.** Bronchopulmonary Dysplasia.
483 *Am J Resp Crit Care Medicine* 163: 1723–1729, 2001. doi: 10.1164/ajrcem.163.7.2011060.
- 484 27. **Escourrou G, De Luca D.** Lung ultrasound decreased radiation exposure in preterm
485 infants in a neonatal intensive care unit.
486 *Acta Paediatr* 105: e237–e239, 2016. doi: 10.1111/apa.13369.
- 487 28. **von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP,**
488 **STROBE Initiative.** The Strengthening the Reporting of Observational Studies in Epidemiology
489 (STROBE) statement: guidelines for reporting observational studies.
490 *J Clin Epidemiol* 61: 344–349, 2008. doi: 10.1016/j.jclinepi.2007.11.008.
- 491 29. **Dell’Orto V, Bourgeois-Nicolaos N, Rouard C, Romain O, Shankar-Aguilera S,**
492 **Doucet-Populaire F, De Luca D.** Cell Count Analysis from Nonbronchoscopic Bronchoalveolar
493 Lavage in Preterm Infants. *J Pediatr* 200:30-37.e2, 2018. doi: 10.1016/j.jpeds.2018.04.074.
- 494 30. **Cappa P, Sciuto SA, Silvestri S.** Experimental evaluation of errors in the measurement of
495 respiratory parameters of the newborn performed by a continuous flow neonatal ventilator.
496 *J Med Eng Technol* 30:31-40, 2006. doi: 10.1080/03091900500040295.
- 497 31. **Ottaviani V, Veneroni C, Dell’Orto V, Lavizzari A, Ventura ML, Tossici M,**
498 **Maroszynska I, Mosca F, Tagliabue P, De Luca D, Dellacà RL.** Accuracy of volume and pressure
499 delivery by mechanical ventilators in use in neonatal intensive care units: A quality control study.
500 *Pediatr Pulmonol* 55: 1955–1962, 2020. doi: 10.1002/ppul.24852.
- 501 32. **De Luca D, Piastra M, Conti G.** Technical problems with dynamic compliance
502 evaluation in neonates and infants.
503 *Intensive Care Med* 38: 1082–1083, 2012. doi: 10.1007/s00134-012-2522-3.
- 504 33. **Richter J, Toelen J, Vanoirbeek J, Kakigano A, DeKoninck P, Verbeken E, Deprest J.**
505 Functional assessment of hyperoxia-induced lung injury after preterm birth in the rabbit.
506 *Am J Physiol Lung Cell Mol Physiol* 306: L277–L283, 2014. doi: 10.1152/ajplung.00315.2013.

- 507 34. **McGraw KO, Wong SP.** Forming inferences about some intraclass correlation
508 coefficients. *Psychol Methods* 1: 30–46, 1996. doi: 10.1037/1082-989X.1.1.30.
- 509 35. **Liu X, Lv X, Jin D, Li H, Wu H.** Lung ultrasound predicts the development of
510 bronchopulmonary dysplasia: a prospective observational diagnostic accuracy study.
511 *Eur J Pediatr* 2021 Mar 23. doi: 10.1007/s00431-021-04021-2.
- 512 36. **Salaets T, Aertgeerts M, Gie A, Vignero J, de Winter D, Regin Y, Jimenez J, Vande
513 Velde G, Allegaert K, Deprest J, Toelen J.** Preterm birth impairs postnatal lung development in the
514 neonatal rabbit model. *Respir Res* 21: 59, 2020. doi: 10.1186/s12931-020-1321-6.
- 515 37. **Chiumello D, Mongodi S, Algieri I, Vergani GL, Orlando A, Via G, Crimella F,
516 Cressoni M, Mojoli F.** Assessment of Lung Aeration and Recruitment by CT Scan and Ultrasound
517 in Acute Respiratory Distress Syndrome Patients.
518 *Crit Care Med* 46: 1761–1768, 2018. doi: 10.1097/CCM.0000000000003340.
- 519 38. De Luca D. Semiquantitative lung ultrasound scores are accurate and useful in critical
520 care, irrespective of patients' ages: The power of data over opinions.
521 *J Ultrasound Med* 39:1235-1239, 2020. doi: 10.1002/jum.15195.
- 522 39. **Manzano RM, Mascaretti RS, Carrer V, Haddad LB, Fernandes AR, Reyes AMA,
523 Rebello CM.** A Hyperoxic Lung Injury Model in Premature Rabbits: The Influence of Different
524 Gestational Ages and Oxygen Concentrations.
525 *PLoS One* 9: e95844, 2014. doi: 10.1371/journal.pone.0095844.
- 526 40. **Coalson JJ.** Pathology of Bronchopulmonary Dysplasia.
527 *Semin Perinatol* 30: 179–184, 2006. doi: 10.1053/j.semperi.2006.05.004.
- 528 41. **Kovar J, Sly PD, Willet KE.** Postnatal alveolar development of the rabbit.
529 *J Appl Physiol* 93: 629–635, 2002. doi: 10.1152/jappphysiol.01044.2001.
- 530 42. **Cattarossi L, Copetti R, Poskurica B, Miserocchi G.** Surfactant administration for
531 neonatal respiratory distress does not improve lung interstitial fluid clearance: echographic and
532 experimental evidence. *J Perinat Med* 38: 557-563, 2010. doi: 10.1515/jpm.2010.096.

- 533 43. **Baraldi E, Filippone M, Trevisanuto D, Zanardo V, Zacchello F.** Pulmonary function
534 until two years of life in infants with bronchopulmonary dysplasia.
535 *Am J Respir Crit Care Med* 155: 149–155, 1997. doi: 10.1164/ajrcem.155.1.9001304.
- 536 44. **Robin B, Kim Y-J, Huth J, Klocksieben J, Torres M, Tepper RS, Castile RG, Solway
537 J, Hershenson MB, Goldstein-Filbrun A.** Pulmonary function in bronchopulmonary dysplasia.
538 *Pediatr Pulmonol* 37: 236–242, 2004. doi: 10.1002/ppul.10424.
- 539 45. **Raimondi F, Yousef N, Migliaro, F, Capasso L, De Luca D.** Point-of-care lung
540 ultrasound in neonatology: classification into descriptive and functional applications.
541 *Pediatr Res* 2018 Jul 20:1–8. doi: 10.1038/s41390-018-0114-9.
- 542 46. **Park JH, Chang YS, Sung S, Ahn SY, Park WS.** Trends in Overall Mortality, and
543 Timing and Cause of Death among Extremely Preterm Infants near the Limit of Viability.
544 *PLoS One* 12(1):e0170220, 2017. doi: 10.1371/journal.pone.0170220.

545

546

547

548 **Figure 1. Lung ultrasound procedure in newborn rabbits.** Both lungs were entirely scanned in
549 each animal (**Panel A**) and, since the probe was relatively large compared to the animal chest, the
550 evaluation was done on the whole hemithorax (i.e., without any division in chest areas (16)) both
551 transversally (**Panel B₁**) and longitudinally (**Panel B₂**). rLUS was calculated according to the
552 classical semiology pattern used for the neonatal lung ultrasound score (17), that is, assigning 0-to-3
553 points (**Panel C-F**). A 0 indicates A-pattern (defined by the presence of A-lines only, white triangles,
554 representative of normally aerated zones); 1, B-pattern (defined as the presence of ≥ 3 well-spaced B-
555 lines, white arrows, indicative of zones with interstitial edema); 2, severe B-pattern (defined as the
556 presence of crowded and coalescent B-lines, white arrows with parentheses, with or without
557 consolidations limited to the subpleural space, that is zones with alveolar edema); and 3, extended
558 consolidations (that is zones with total loss of aeration; white star). If the lung appearance was not
559 homogenous, several pictures were registered to capture all lung ultrasound features and their
560 evaluation was averaged. Pictures refer to a hyperoxia-exposed preterm rabbit, but the same
561 technique was used both in preterm and term rabbits.

562

563 **Figure 2. Conformity of lung ultrasound features interpretation to calculate rLUS.** Observer 1
564 and 2, respectively, indicate the investigator performing animal care and the neonatologist expert in
565 lung ultrasound who independently evaluated the lung ultrasound images. Horizontal lines depict
566 medians and 25th-75th percentiles and analyzed with intra-class correlation coefficient and Mann-
567 Whitney test. Experiments were performed in 25 hyperoxia-exposed preterm rabbits. rLUS is a
568 dimensionless number. **Abbreviations:** rLUS: rabbit lung ultrasound score.

569

570 **Figure 3. Illustrative pictures of abnormal lung ultrasound features in hyperoxia-exposed**
571 **preterm rabbits and human neonates with evolving BPD.** Pictures on the left- and right-side have
572 been taken from rabbits and infants, respectively. Panels A and B show a B-pattern (interstitial);
573 panels C and D show a severe B-pattern (alveolar) and panels E and F show extended consolidation

574 with loss of lung aeration. Lung ultrasound findings were very and equally heterogeneous both in
575 preterm rabbits and in neonates.

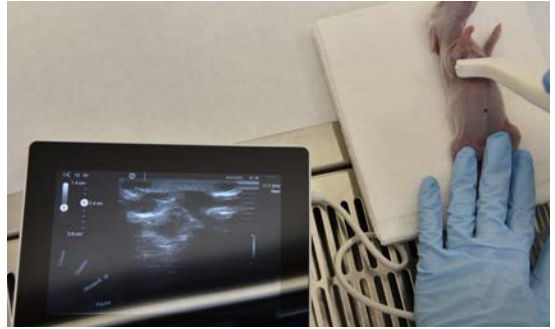
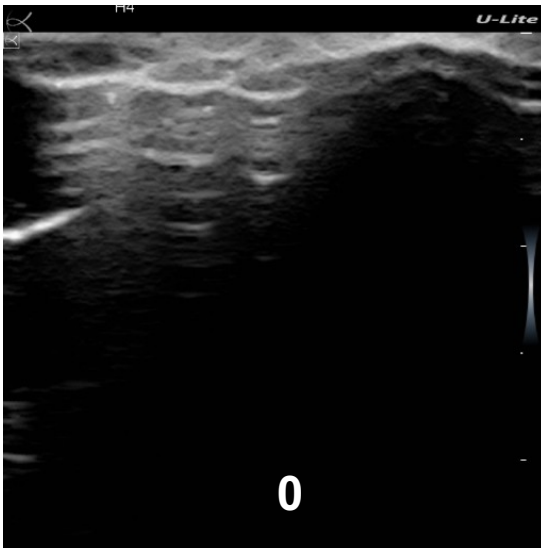
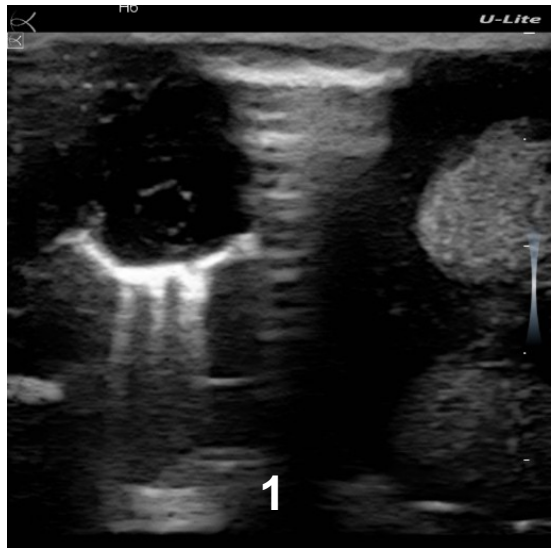
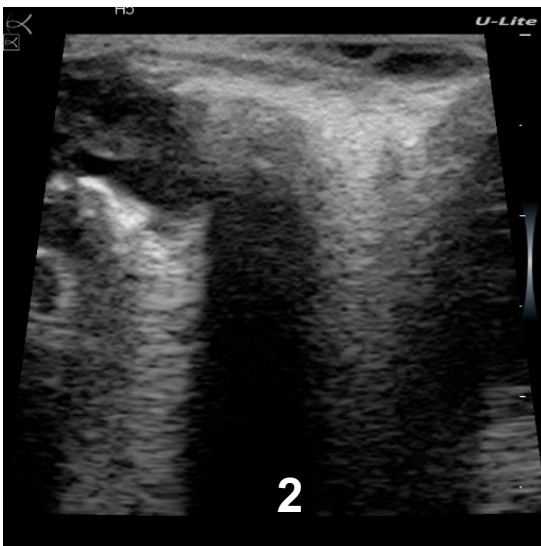
576

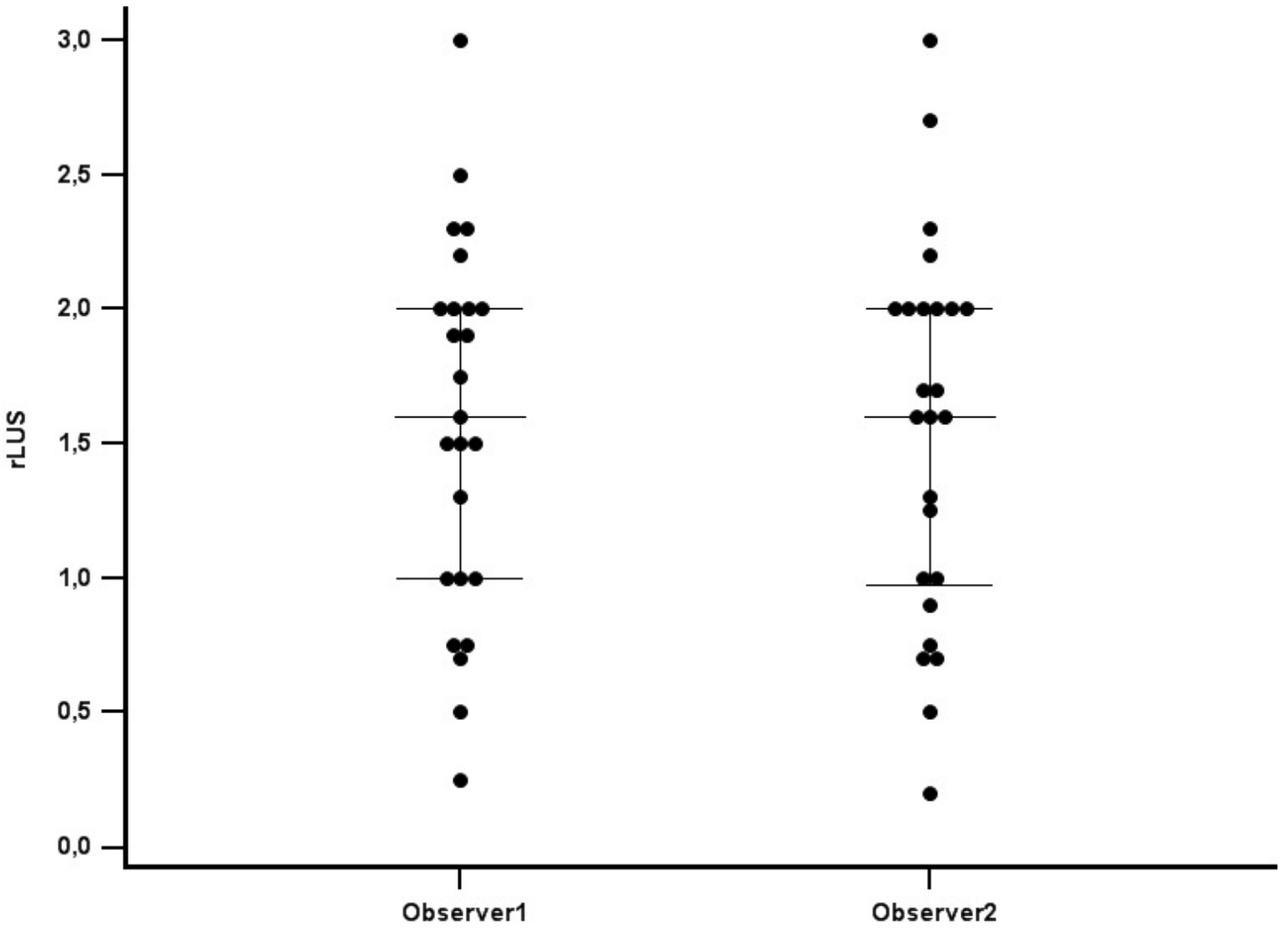
577 **Figure 4. Relationship between lung ultrasound scores and lung mechanics measurements in**
578 **hyperoxia-exposed preterm rabbits (n=25; panel A-B) and neonates with evolving BPD (n=25;**
579 **panel C-D).** Spearman correlation coefficients and their *p*-values are shown. The hatched curve
580 shows the tendency and represents the best fitting data curve generated with local smoother
581 regression. Panel A and B represent the correlation between rLUS and airway resistance or dynamic
582 lung compliance, respectively. Panel C and D represent the correlation between the classical neonatal
583 LUS and airway resistance or dynamic lung compliance, respectively. LUS and rLUS are
584 dimensionless numbers. **Abbreviations:** Cdyn: dynamic lung compliance; Raw: airway resistance;
585 LUS: lung ultrasound score; rLUS: rabbit lung ultrasound score.

586

587 **Figure 5. Histology and lung ultrasound features in hyperoxia-exposed preterm rabbits (left**
588 **side; n=25) and term rabbits kept in normoxia (right side; n=13).** Illustrative hematoxylin and
589 eosin staining of a sagittal section of the right lung from one animal per group are shown with 2x
590 (panel A-B) and 10x magnification (panel C-D). There are clear differences between the groups, with
591 hyperoxia-exposed preterm rabbits showing inflammatory cell infiltration, larger alveoli, and
592 thickened septa. Panel E-F show illustrative lung ultrasound images from one animal per group: the
593 hyperoxia-exposed preterm rabbit has an alveolar pattern with confluent B-lines, while the control
594 rabbit has a normal lung appearance with only A-lines. Panel G shows morphometric and lung
595 ultrasound score data in the two groups. rLUS is a dimensionless number. **Abbreviations:** Lm: mean
596 linear intercept; rLUS: rabbit lung ultrasound score.

597

A**B₁****B₂****C****D****E****F**

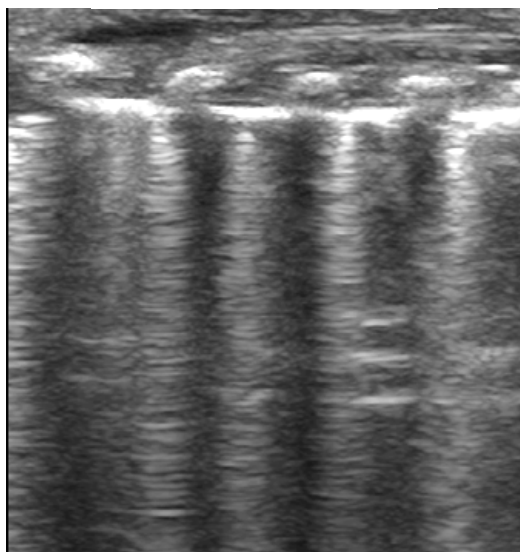




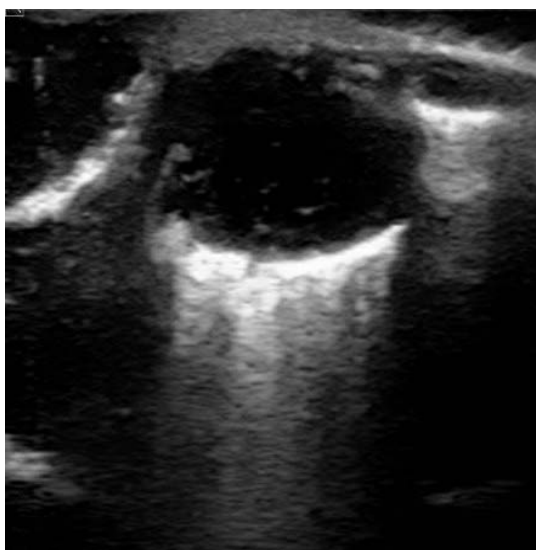
A



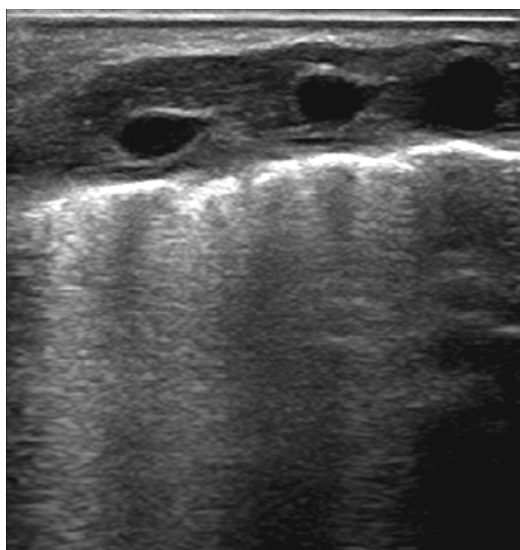
B



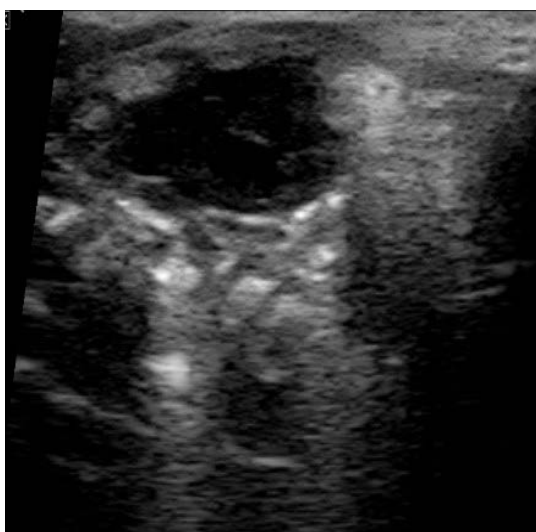
C



D

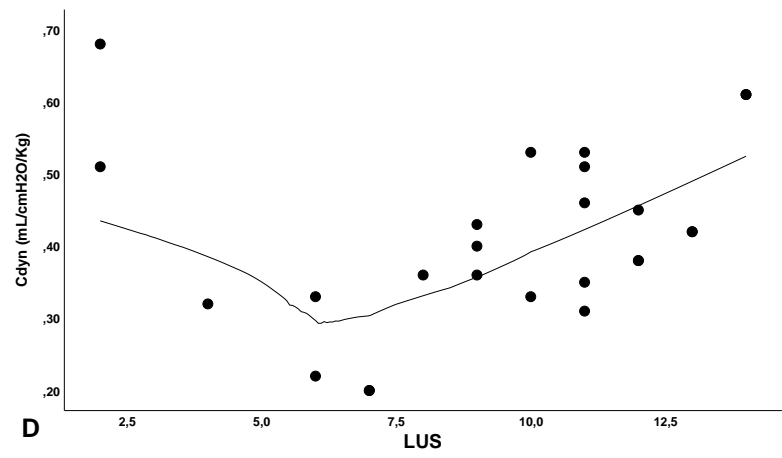
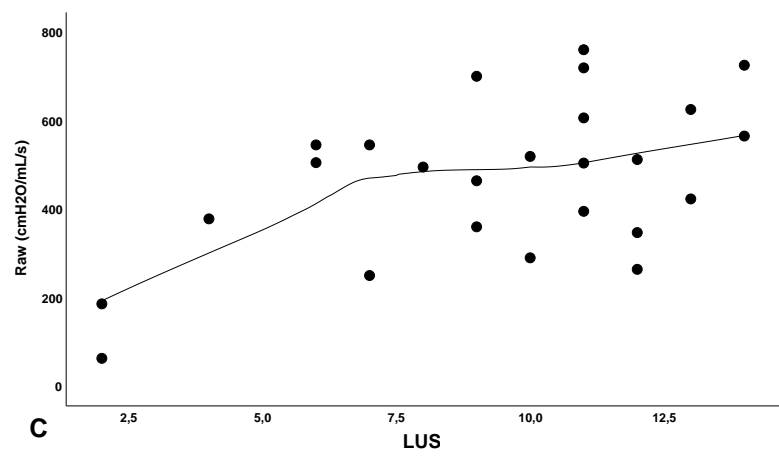
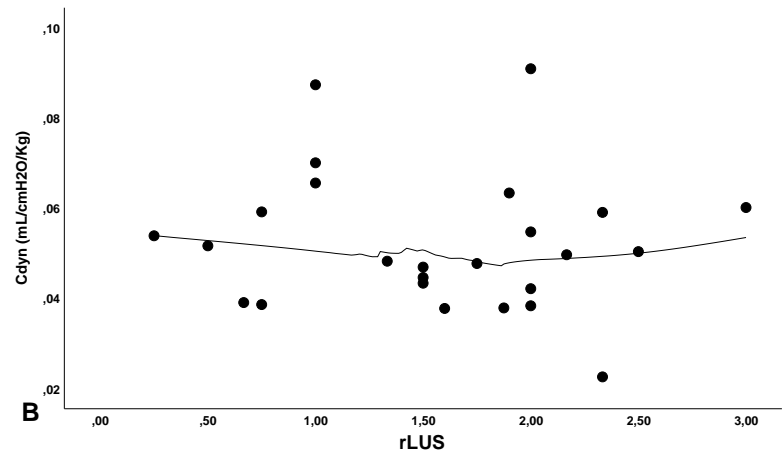
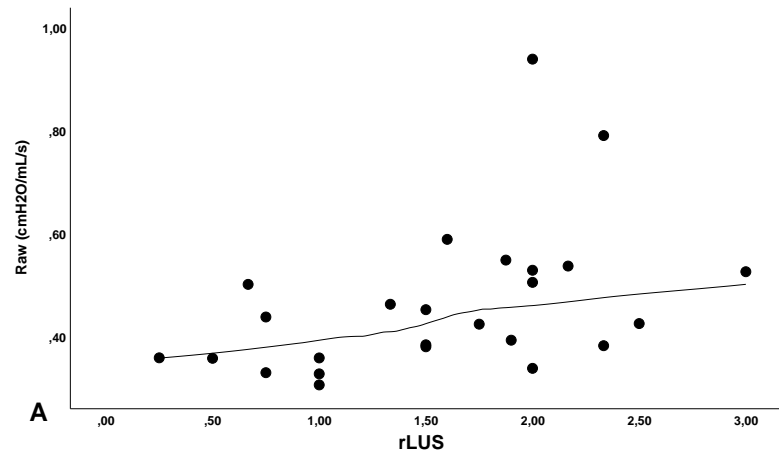


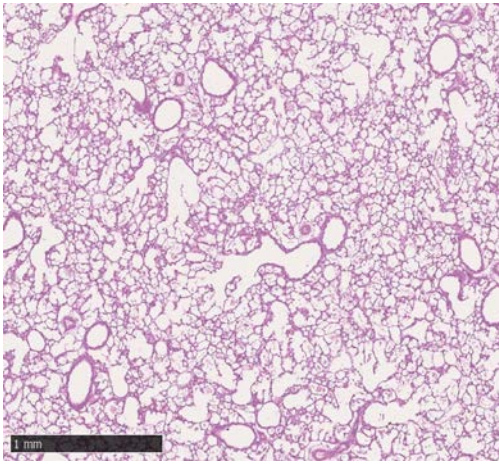
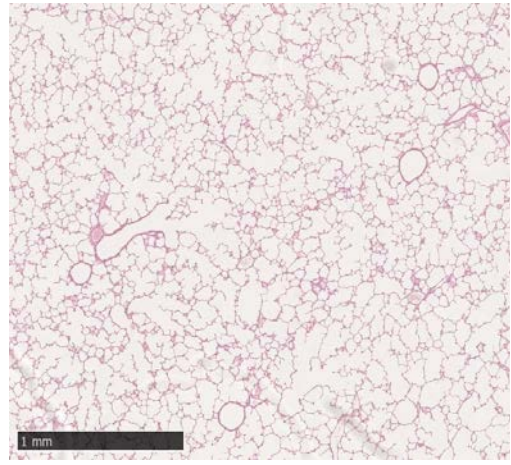
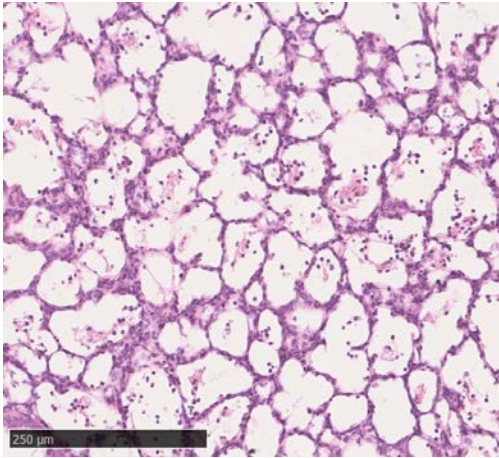
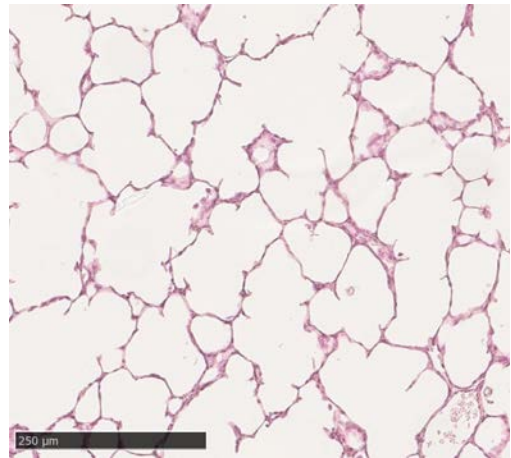
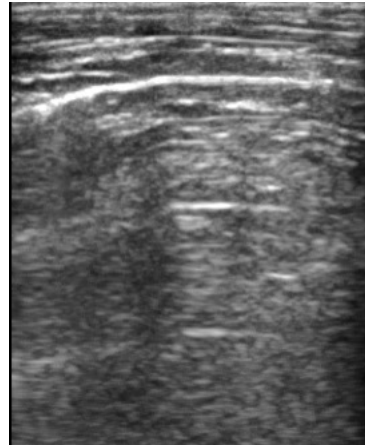
E



F





A**B****C****D****E****F****G**

**Preterm
(hyperoxia-exposed)**

**Term
(normoxia)**

p**Lm (μm)**

84 (4.9)

72 (5.5)

<0.0001

rLUS

1.6 [1-2]

0 [0-0]

<0.0001

G	Preterm (hyperoxia-exposed)	Term (normoxia)	<i>p</i>
Lm (μm)	84 (4.9)	72 (5.5)	<0.0001
rLUS	1.6 [1-2]	0 [0-0]	<0.0001

Table 1. Characteristics of hyperoxia-exposed preterm rabbits and human neonates. Data are expressed as mean (standard deviation), median [interquartile range] and number (%). Weight-D7 and Weight-D14 indicate the weight at the 7th and 14th day of life, respectively. rLUS-D7 and LUS-D14 indicate the rabbit and the neonatal lung ultrasound score at the 7th and 14th day of life, respectively. Apgar, CRIB-II, LUS and rLUS are dimensionless numbers. Prenatal steroids prophylaxis is considered if complete, that is, if two 12mg betamethasone doses were administered 24h apart and within 7 days before the delivery.

Abbreviations: CRIB-II: critical risk index for babies; LUS: neonatal lung ultrasound score; NICU: neonatal intensive care units; rLUS: rabbit lung ultrasound score.

Preterm rabbits (n=25)	
Birth weight (grams)	37 (1.01)
Weight-D7 (grams)	49.3 (1.44)
rLUS-D7	1.5 [0.25-3]
Preterm neonates (n=25)	
Gestational age (weeks)	25.8 (1.01)
Birth weight (grams)	759 (115)
Weight-D14 (grams)	898 (125)
Prenatal steroids prophylaxis	17 (68%)
Male Sex	14 (63.6%)
5' Apgar score	9 [5.5-8.5]
CRIB-II score	12 [11-13]
LUS-D14	7 [8-11]
NICU stay (days)	101 [96-130]

Table 2. Lung mechanics variables in preterm rabbits and neonates. Data are expressed as mean (standard deviation). **Abbreviations:** Cdyn: dynamic compliance, Raw: airway resistance.

Preterm rabbits (n=25)	
Raw (cmH ₂ O/mL/sec)	0.5 (0.1)
Cdyn (mL/cmH ₂ O/kg)	1.07 (0.3)
Inspiratory capacity (mL/kg)	20.6 (6.2)
Tissue damping (cmH ₂ O/mL)	3.1 (0.7)
Elastance (cmH ₂ O/mL)	12 (2.9)
Preterm neonates (n=25)	
Raw (cmH ₂ O/L/sec)	470 (176)
Cdyn (mL/cmH ₂ O/kg)	0.32 (0.1)