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Neonatal ACE inhibition in rats interferes with lung development
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Summary
The renin–angiotensin system (RAS) is developmentally up-regulated and it is essential for kidney development in several species. Given the fact that the rat lung undergoes postnatal development, the mammalian lung possesses the highest angiotensin-converting enzyme (ACE) levels and ACE activity increases during the first weeks postpartum, we tested the hypothesis that ACE inhibition influences postnatal lung development. Rats were given the ACE inhibitor enalapril (10 mg kg−1) from 0 to 9 days of age and their lungs were examined at day 4 and 9. Lung structure was evaluated by means of light microscopy, and surface tension of bronchoalveolar lavage fluid was measured by means of a Wilhelmy balance. Neonatal ACE inhibition lowered the surface tension of bronchoalveolar lavage fluid and caused widening of respiratory airspaces and thinning of alveolar septa. Our results suggest that early postnatal ACE inhibition in rats interferes with lung development.

Introduction
The activity and distribution of the renin–angiotensin system (RAS) are developmentally regulated in a tissue-specific manner, and angiotensin II (Ang II) can act as a modulator of growth in a variety of cells and tissues (Gomez, 1990; Touyz & Schiffrin, 2000). The RAS has also been shown to be critically important in development. There is ample evidence for its mandatory role in kidney development (Friberg et al., 1994; Tufro-McReddie et al., 1995; Guron & Friberg, 2000). Different components of the RAS, including angiotensin-converting enzyme (ACE) and both angiotensin type 1 (AT1) and type 2 (AT2) receptors, are expressed in lung endothelial and type II epithelial cells, respectively (Morrell et al., 1996; Wang et al., 1999). The mammalian lung possesses the highest ACE levels (Esther et al., 1996) and ACE activity increases during the first weeks postpartum (Wallace et al., 1978). Rats are born with immature lungs and, within the first two postnatal weeks, the alveolization (Scheuermann et al., 1988), together with subcellular reorganization in type II epithelial cells (Young et al., 1991) and changes in surfactant homeostasis (Griese et al., 1999), occurs in rats. The aim of this study was to test the hypothesis that ACE inhibition (ACEI) influences lung development. Hence, rats were given ACEI during 9 days starting at day 0 after birth and their lungs were examined at day 4 and 9. Structural changes in ACEI lung were evaluated at light microscopical level, and surface tension of bronchoalveolar lavage fluid (BAlF), a reflector of quantitative and/or qualitative abnormalities of alveolar surfactant, was measured by means of a Wilhelmy balance (Schmekel et al., 1992).

Methods
General procedures
Time-mated, female Wistar rats (B & K Universal AB, Sollentuna, Sweden) were transported to our facility on the 14th day of pregnancy. They were observed carefully for determination of the day of delivery. Both male and female pups were included in the study. Weight matched pups were divided into two groups receiving daily intraperitoneal injections of either enalapril maleate (10 mg kg−1; Sigma-Aldrich Sweden AB) or isotonic saline vehicle in equivalent volumes of 10 ml kg−1 from day 0 (within 12 h after birth) to day 9. We chose 10 mg kg−1 dose of enalapril maleate, which was demonstrated to inhibit nearly completely ACE activity (Guron et al., 1999). Throughout the study rats had free access to standard rat chow and tap water and were kept in rooms with a controlled temperature of 24°C and a
Light microscopy and semiquantitative assessment

For microscopical evaluation, seven to nine pups from enalapril maleate and saline treated groups were anaesthetized with sodium pentobarbital (60 mg kg\(^{-1}\), intraperitoneally; Apoteksbolaget, Umeå, Sweden) at day 4 and 9 after birth. After thoracotomy, the lungs were excised and immersion-fixed in 4% paraformaldehyde. The upper, middle and lower part of the left lung was cross-dissected into ≈4 mm thick planes and their fixation was continued for 24 h. After fixation planes were dehydrated through an ethanol series and all three planes from each lung were embedded in paraffin en bloc. Keeping the distance of 50 μm in between, three 3-μm-thick serial sections were cut and stained with haematoxylin and eosin. Nine sections from each lung were used for the semiquantitative assessment of lung structural changes. Assessments were made by an investigator blind to treatment group. The presence of wider respiratory airspaces and thinner alveolar septa was scored semiquantitatively with the use of arbitrary scale: 1, mild; 2, moderate; and 3, severe changes.

Measurement of surface tension of bronchoalveolar lavage fluid

For measurements of surface tension of BALF, seven to nine pups from enalapril maleate and saline treated groups were anaesthetized with sodium pentobarbital (60 mg kg\(^{-1}\), i.p.) at day 4 and 9 after birth. After thoracotomy the lungs were washed gently three times with 37°C saline (30 ml kg\(^{-1}\)) and BALF aliquots were pooled, yielding in 2–2.5 ml of lavage fluid. The lavage fluid was centrifuged at 150 g for 10 min to remove any cells and frozen at −20°C. Surface tension of BALF was measured with a Wilhelmy balance (Biegler Electronic, Mauerbolaget, Umeå, Sweden) at day 4 and 9 after birth. A teflon trough (115·73 mN m\(^{-1}\)) measured with a Wilhelmy balance (Biegler Electronic, Mauerbolaget, Umeå, Sweden) at day 4 and 9 after birth. After thoracotomy, the lungs were excised and immersion-fixed in 4% paraformaldehyde. The upper, middle and lower part of the left lung was cross-dissected into ≈4 mm thick planes and their fixation was continued for 24 h. After fixation planes were dehydrated through an ethanol series and all three planes from each lung were embedded in paraffin en bloc. Keeping the distance of 50 μm in between, three 3-μm-thick serial sections were cut and stained with haematoxylin and eosin. Nine sections from each lung were used for the semiquantitative assessment of lung structural changes. Assessments were made by an investigator blind to treatment group. The presence of wider respiratory airspaces and thinner alveolar septa was scored semiquantitatively with the use of arbitrary scale: 1, mild; 2, moderate; and 3, severe changes.

Surface tension of bronchoalveolar lavage fluid

Enalapril treatment lowered minimum ($\gamma_{\text{min}}$) surface tension of BALF, as measured with 200 μl quantity (Fig. 3). The maximum ($\gamma_{\text{max}}$) surface tension of BALF did not differ between groups either on postnatal day 4 (70±3±1·7 versus 68±4±2·6 mN m\(^{-1}\), in control and enalapril treated rats, respectively) or day 9 (69±4±3·2 versus 69±9±2·1 mN m\(^{-1}\), in control and enalapril treated rats, respectively).

Discussion

The main finding of this study was that ACEI decreased surface tension of BALF, reflecting higher amount of alveolar surfactant, in neonatal rats on day 4 and 9. This was paralleled by structural alterations in the lungs. Thus, early postnatal ACE inhibition in rats interferes with lung development.

Surface tension of BALF, as measured in this study, mirrors the functional integrity of alveolar surfactant system. Pulmonary surfactant is a surface-active material composed of phospholipid-rich lipoproteins that reduce surface tension at the alveolar surface, promoting lung expansion during inspiration and preventing lung collapse during expiration (De Paepe et al., 1998). The lower minimum surface tension of BALF in enalapril treated rats suggests that there is more surface-active surfactant in alveolar space, which, in turn, could result in lung structural alterations, characterized by thinner alveolar septa and wider respiratory airspaces, as evident from our study. Pulmonary surfactant is synthesized, stored, secreted, taken up and catabolized by type II pneumocytes (Griese et al., 1999). The lamellar body within type II pneumocyte is the final secretory structure of pulmonary surfactant (Voorhout et al., 1993). In a pilot study, we evaluated the morphology of type II pneumocytes at ultrastructural level and observed no alterations in enalapril-subjected lungs, implying preserved intracellular stores of surfactant.
Collectively, it appears that early postnatal ACE inhibition increases the alveolar surfactant pool. At the present time, we could only speculate about the mechanism of the changes we observed because we have not established whether the alveolar surfactant pool is increased due to enalapril-stimulated secretion or enalapril-inhibited uptake or both. Our finding of the disturbance in alveolar surfactant system in enalapril-treated rats suggests a role for ACE in the regulation of surfactant homeostasis in developing rat lungs. In this context, there is evidence to suggest that ACE inhibition results in increased levels of bradykinin and/or prostaglandins (PGs) (Buttar, 1997). Prostaglandins, in turn, enhance production and secretion of surfactant by type II pneumocytes (Oyarzun & Clements, 1978; Nagai et al., 1995). Therefore, it is possible that the disturbance in surfactant homeostasis following neonatal ACEI is due to increased PGs, such as PGE\textsubscript{2} (Marin-Castano et al., 2002). Indeed, rat PGE\textsubscript{2} receptors are expressed in lung tissue (Nemoto et al., 1997), and PGE\textsubscript{2} is a potent local mediator of cell growth and differentiation in various tissues, and it plays a role in early postnatal lung development (Nagai et al., 1995).

In summary, ACE regulates surfactant homeostasis in immature rat lung and, therefore, may play an important role in lung development.
Values are mean values ± SD (n = 7–9 per group and time point).

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