ERJ open research
THE BEST IN OPEN ACCESS BASIC, TRANSLATIONAL & CLINICAL RESPIRATORY RESEARCH

Early View

Original article

Preclinical evaluation of the ENaC inhibitor BI 1265162 for treatment of cystic fibrosis

Peter Nickolaus, Birgit Jung, Juan Sabater, Samuel Constant, Abhya Gupta

Please cite this article as: Nickolaus P, Jung B, Sabater J, *et al*. Preclinical evaluation of the ENaC inhibitor BI 1265162 for treatment of cystic fibrosis. *ERJ Open Res* 2020; in press (https://doi.org/10.1183/23120541.00429-2020).

Preclinical evaluation of the ENaC inhibitor BI 1265162 for treatment of cystic fibrosis

Peter Nickolaus PhD[1], Birgit Jung MD[1], Juan Sabater MD[2], Samuel Constant PhD[3], Abhya Gupta MD[1]

[1]Boehringer Ingelheim, Biberach, Germany; [2]Mount Sinai Medical Center, Miami Beach, Florida, USA; [3]Epithelix Sàrl, Plan-les-Ouates, Switzerland.

Corresponding author: Peter Nickolaus

Email: peter.nickolaus@boehringer-ingelheim.com

Funding: This work was supported by Boehringer Ingelheim International GmbH. Medical writing assistance, in the form of the preparation and revision of the manuscript, was supported financially by Boehringer Ingelheim, and provided by Lee Kempster and Ishmam Nawar of MediTech Media (London, UK) under the authors' conceptual direction and based on feedback from the authors. Findings from the studies were presented in the European Cystic Fibrosis Conference, 5–8 June 2019, Liverpool, United Kingdom.

Keywords: Preclinical, epithelial sodium channel inhibitor, cystic fibrosis, mucociliary clearance, mutation-agnostic

Running head: Preclinical evaluation of BI 1265162

Word count: 3,331/3,000

Abstract

Background

Epithelial sodium channel (ENaC) is an important regulator of airway surface liquid volume; ENaC is hyperactivated in cystic fibrosis (CF). ENaC inhibition is a potential therapeutic target for CF. Here, we report *in vitro* and *in vivo* results of BI 1265162, an inhaled ENaC inhibitor currently in Phase II clinical development, administered via the Respimat® Soft Mist™ inhaler.

Methods

In vitro inhibition of sodium ion (Na^+) transport by BI 1265162 was tested in mouse renal collecting duct cells (M1) and human bronchial epithelial cells (NCI-H441); inhibition of water transport was measured using M1 cells. *In vivo* inhibition of liquid absorption from rat airway epithelium and acceleration of mucociliary clearance (MCC) in sheep lungs were assessed. Fully differentiated normal and CF human epithelium was used to measure the effect of BI 1265162 with or without ivacaftor and lumacaftor on water transport and MCC.

Results

BI 1265162 dose-dependently inhibited Na^+ transport and decreased water resorption in cell line models. BI 1265162 reduced liquid absorption in rat lungs and increased MCC in sheep. No effects on renal function were seen in the animal models. BI 1265162 alone and in combination with CF transmembrane conductance regulator (CFTR) modulators decreased water transport and increased MCC in both normal and CF airway human epithelial models and also increased the effects of CFTR modulators in CF epithelium to reach the effect size seen in healthy epithelium with ivacaftor/lumacaftor alone.

Conclusion

These results demonstrate the potential of BI 1265162 as a mutation agnostic, ENaC-inhibitor-based therapy for CF.

Word count: 250/250

Take-home message

ENaC inhibition is a potential strategy for a mutation-agnostic therapy in CF. We demonstrate, in preclinical studies, that BI 1265162 is a potent ENaC inhibitor, alone and in synergy with CFTR modulators, supporting Phase I clinical development.

Lay Summary

BI 1265162 is a type of medication that blocks the action of a protein called epithelial sodium channel, or ENaC. Taking this medication regularly may keep the surface of the airways hydrated, which could help to make mucus in the lungs less thick and keep the airways clear in patients with cystic fibrosis (CF).

In this study, BI 1265162 was tested on cellular and animal models. This important stage of research, called preclinical studies, is carried out before testing in humans, and can help to see if the compound is likely to be safe and effective in humans.

Results from preclinical testing showed that BI 1265162 was effective at reducing sodium ion and water transport in cell models. In rat lungs, BI 1265162 helped to stop liquid being moved out of the airways, thereby keeping them hydrated. In sheep, the compound made it easier to keep airways clear. When tested together with CF transmembrane conductance regulator modulators – a type of medication that is designed to correct the faulty protein made in CF – BI 1265162 increased the effect of this medication in cells taken from a patient with CF.

These early results show that BI 1265162 has potential for treating CF, either on its own or in combination with other medicines. Due to these promising results, studies with BI 1265162 in patients with CF are now underway.

Word count: 226

Introduction

Cystic fibrosis (CF) is an autosomal recessive genetic disease caused by mutations in the CF transmembrane conductance regulator (*CFTR*) gene [1], which facilitates chloride secretion across apical cell membranes. CFTR and the epithelial sodium channel (ENaC) together maintain a finely tuned homeostatic mechanism to keep airway surfaces hydrated [2, 3]. Sufficient airway surface hydration facilitates mucociliary clearance (MCC), which is needed for a normal lung environment [4, 5]. In CF airways, the marked reduction of functional CFTR leads to reduction in airway surface liquid (ASL) height, dehydration of airway surfaces and sticky mucus, leading to impaired MCC, mucous plugging, neutrophilic infiltration, and chronic bacterial infection [4-6]. This can cause airway obstruction/destruction, and ultimately respiratory failure and death [7].

Previous pulmonary treatments of CF have targeted downstream effects of the disease, such as mucous plugging and infection, as well as providing supportive care. More recent corrective therapy options target the CFTR defects [8-10]. However, with over 2,000 identified mutations in the *CFTR* gene [11] that could lead to either complete absence of the CFTR protein or a malformed CFTR protein [12], targeting CFTR is currently not an option for all patients with CF [7]. At least 10% of patients with CF are unable to receive CFTR modulator therapy due to unsuitable genotype [13]. In addition, despite the best available therapy targeting specific genotypes of CF, patients continue to have exacerbations, with room for improvement in lung function [10, 14], and inflammation is not always reversible with current therapies [15]. Therapies that work on pathways independent of CFTR correction (additive) or synergistic to CFTR modulation would provide additional

therapeutic benefit. A combination of multiple therapies will optimally improve quality of life and best prolong patient survival [5].

An ion-transporting pathway that could be targeted to ameliorate the impact of CF is the epithelial sodium channel (ENaC) pathway. ENaC facilitates sodium ion (Na^+) and, as consequence, water resorption from the apical surface [16], and plays an important role in ASL volume regulation and effective MCC [17]. Hyperactivation of ENaC is known in CF, potentially as a consequence of both an increase in channel number and an increase in open probability of the channel [18]. This leads to increased absorbance of Na^+ followed by water resorption from the apical surface, causing reduced ASL height, dehydrated mucus and compressed cilia, subsequently resulting in poor MCC [16, 19]. It is thought that the CFTR protein may play a role in ENaC modulation; however, the nature of this interaction is not fully understood [5, 20].

ENaC inhibition provides a mutation-agnostic therapeutic approach (i.e. independent of the type of underlying *CFTR* mutation) that can improve ASL height, mucus hydration and MCC in airways [5, 21]. This is predicted to be synergistic or at least additive with CFTR modulators [5]. Unfortunately, development of ENaC inhibitors so far has not translated into clinical success [16], likely due to poor potency, inadequate dosing and/or deposition by inhalation, induced hyperkalaemia, short study duration, non-study-related exacerbations or poor endpoint sensitivity.

BI 1265162 is an inhaled ENaC inhibitor that is expected to provide a mutation-agnostic approach for treating CF. It is administered via the Respimat® Soft Mist™ inhaler which is a handheld, propellant-free device that produces a slow-moving, long-lasting mist helping medication to reach deep into the lungs [22]. BI 1265162 is

currently in Phase II clinical development. Here, we report the results from *in vitro* experiments and animal models designed to establish the clinical potential of BI 1265162 for the treatment of CF.

Methods

A brief summary of methods is given below. For detailed methodology, see the online supplement to this article, available at:

In vitro inhibition of Na^+ transport

The inhibition of Na^+ transport by BI 1265162 was tested in a mouse renal collecting duct cell line (M1) and a human bronchial epithelial cell line (NCI-H441).

M1 and NCI-H441 cells were cultivated on polyester Transwell® filters to electrically tight monolayers. ENaC expression was then upregulated with dexamethasone to achieve sufficient short circuit current (I_{SC}) [23]. The apical bath solution was removed to create an air–liquid interface and filters containing cell layers were inserted into an Ussing chamber. BI 1265162 was administered at final concentrations of 10^{-10}, 10^{-9}, 10^{-8}, 10^{-7} and 10^{-6} M in a stepwise manner to the apical solution of each filter. At the end of each experiment I_{SC} was measured by inhibiting Na^+ transport with 3 µM amiloride (maximum inhibition) as previously described [24, 25]. Differences in I_{SC} after addition of test compounds were compared against maximum inhibition and the inhibition concentration that reduced the effect by 50% (IC_{50}) was calculated. M1 experiments were repeated four times and H441 experiments were repeated twice (n=5 for each experiment).

In vitro inhibition of water resorption

ENaC-mediated water transport with and without BI 1265162 was measured in electrically tight monolayers of M1 cells using the Transwell® system (E-figure 1). After culture, the apical liquid volume from the M1 cell layers was carefully aspirated and replaced with either 0.9% saline control or 0.9% saline containing BI 1265162. For determination of volume of water on the apical side, tritiated water was then added and mixed with the apical volume of the Transwell®, and water resorption measured by scintigraphy using a radiometric dilution assay. Experiments were carried out in duplicate.

In vivo inhibition of liquid absorption

Efficacy of BI 1265162 on inhibition of liquid absorption from airway epithelium was determined in male Wistar rats.

Male Wistar rats were anaesthetised with isoflurane prior to intratracheal instillation of test compound or vehicle. Ringer Lactate Solution pH 5 alone or with increasing concentrations (0.03, 0.3, 3 and 10 µg/kg) of BI 1265162 was instilled into the lungs. Three hours after instillation, renal effects of BI 1265162 were determined by measuring serum aldosterone by ELISA. The animals were then sacrificed under anaesthesia, lungs were removed, non-pulmonary tissue was dissected, and the weight of the lung was determined. Inhibition of liquid transport was calculated from lung weights in the treated group versus lung weights of a negative control group, and an untreated control group was used as reference. Experiments were carried out on three separate occasions.

Acceleration of MCC in a sheep model

Stimulation of MCC by BI 1265162 was tested in a sheep model of whole-lung clearance measuring the retention of a radioactive tracer.

Adult ewes (n=2 per dose) were anaesthetised by local application of lidocaine prior to nasal intubation via bronchoscope, then administered doses (0.1, 1.0, and 10 µg/kg) of BI 1265162 or vehicle (deionised water) using an AirLife™ nebuliser. The effects of BI 1265162 or vehicle on MCC were measured by administration of aerosolized technetium-labelled sulphur colloid (^{99m}Tc-SC) followed gamma scintigraphy as previously described [26]. Serial images were obtained over a 2-hour period and counts were obtained from the right lung.

Blood was collected and plasma potassium were determined to assess renal effects of BI 1265162.

In vitro effect on water transport and MCC on CF donor cells

The effect of BI 1265162 (0.1 and 10 µM), with or without ivacaftor (IVA; CFTR corrector; 0.1 µM), lumacaftor (LUM; CFTR potentiator; 3 µM) and isoproterenol (ISO; a non-selective β-adrenoreceptor agonist that upregulates CFTR expression [27]; 100 µM) on water transport, MCC and ciliary beat frequency (CBF) was evaluated using MucilAir™ (a pseudostratified, fully differentiated 3D model of human epithelium on semi-porous membrane inserts) consisting of either primary human bronchial cells isolated from a donor without CF or from a donor with ΔF508 homozygous CF.

Water transport was measured on Days 2 and 5 of the study by weighing the semi-porous membrane inserts containing the cells. MCC was measured on Day 7 by

video-tracking the movements of polystyrene microbeads added to the apical surface of MucilAir™.

Results

BI 1265162 inhibits Na^+ transport in vitro

Stepwise increasing doses of BI 1265162 (10^{-10}–10^{-6} M) in the Ussing chamber assay resulted in a dose-dependent decrease in amiloride-sensitive I_{SC}, reflecting Na^+ transport inhibition in both cell lines (mean IC_{50} with M1 and NCI-H441 cells: $3x10^{-9}$ M and $8x10^{-9}$ M, respectively). Full inhibition was reached at the highest concentration (Figure 1). For amiloride, IC_{50} was $2.10x10^{-7}$ M in M1 cells and $2.38x10^{-7}$ M in NCI-H441 cells.

BI 1265162 inhibits water resorption in vitro

The M1 cells seeded in the Transwell® insert formed a monolayer and transported Na^+ via ENaC from the applied saline out of the apical compartment leading to water resorption. The activity representing 0% transport was calculated to be 3763 disintegrations per minute (dpm) for experiment 1 and 2660 dpm for experiment 2. The mean cell control activity was measured to be 4401 dpm and 3205 for experiments 1 and 2, respectively, resulting in a delta activity corresponding to 100% transport of 638 dpm and 545 dpm and a 1% activity of 6.38 dpm and 5.45 dpm, respectively. Addition of 3 µM BI 1265162 resulted in an inhibition of ENaC-mediated water resorption of 76% (mean of both experiments) compared with saline control (experiment 1: saline, 638 dpm; BI 1265162, 174 dpm [73% decrease]; experiment

2: saline, 545 dpm; BI 1265162, 117 dpm [78% decrease]. Variation between experiments was 5%) (Figure 2).

BI 1265162 inhibits liquid absorption in a rat model

Treatment with BI 1265162 showed a reduction of airway fluid absorption in rat lungs. BI 1265162 doses of 10, 3, 0.3 and 0.03 µg/kg showed an inhibition of 32.9%, 31.3%, 26.2% and 5.9% after 3 hours, respectively (Figure 3). BI 1265162 reduced the liquid absorption from rat lungs with a dose required to reach 50% (ED_{50}), 70% (ED_{70}) and 90% (ED_{90}) of the compound effect of 0.09, 0.18 and 0.54 µg/kg, respectively. Compared with placebo, mean change in aldosterone was 18%, 18%, 45% and –18% for 10, 3, 0.3 and 0.03 µg/kg of BI 1265162, respectively, without dose dependency. No dose-dependent effect on serum aldosterone level was observed in the study.

BI 1265162 accelerates MCC in a sheep model without affecting plasma potassium

In the sheep model of whole-lung clearance, BI 1265162 led to reduction in the retention of radioactive tracer over 2 hours, indicating a higher MCC. The mean differences from vehicle for 1 and 10 µg/kg of BI 1265162 were –12.6% and –19.3%, respectively ($P<0.05$; Figure 4a). ED_{50} to accelerate MCC in sheep was estimated to be 1 µg/kg; ED_{90} was calculated to be 2.3 µg/kg. There were no increases in plasma K^+ over a 24 hours period (Figure 4b).

BI 1265162 attenuates water transport and improves MCC in normal and CF tissues

BI 1265162 dose-dependently induced increases of the inserts' weight, showing reduced water transport from the apical to basolateral compartment in both normal

and CF epithelial cells, either alone, in combination with ISO or IVA/LUM, or both. This indicates clearly that BI 1265162 acts on the liquid homeostasis of airways epithelia. The effect was preserved at Day 5 (Figure 5a). In normal epithelium, MCC was increased by ISO or with a combination of BI 1265162 with other treatments, but not by BI 1265162 alone. In CF epithelium, MCC was almost 0 µm/s with just vehicle added. Addition of BI 1265162 increased MCC dose-dependently, reaching levels from normal epithelium. Addition of IVA/LUM increased MCC alone or together with ISO to approximately 15 and 50 µm/s (approximately 50% of the respective values derived from normal epithelium with the same treatments). Addition of BI 1265162 led to a nearly complete restoration of MCC in CF epithelium also treated with ISO or IVA/LUM (Figure 5b).

Discussion

A comprehensive preclinical analysis demonstrates that BI 1265162 is an effective ENaC inhibitor. BI 1265162 dose-dependently inhibited Na^+ transport and increased water resorption in cell line models. This was further confirmed in animal models, with reduced liquid absorption in rat lungs and increased MCC in sheep. No amiloride-like effects on renal function were demonstrated in the animal models. When tested on normal and CF airway human epithelial models, BI 1265162 alone and in combination with CFTR modulators decreased water transport and increased MCC. BI 1265162 increased the effects of CFTR modulators IVA/LUM to reach the effect size seen in healthy epithelium with IVA/LUM alone.

CFTR has a putative role on ENaC regulation [16, 17]. In healthy airway epithelium, the transepithelial potential difference generated by active ENaC-mediated Na^+

absorption is the driving force for chloride secretion and water absorption. In CF airway epithelium, ENaC is hyperactivated but CFTR function is defective, which leads to an imbalanced secretion and absorption of ions and fluid.[17] This gives rise to the hypothesis that CFTR is not only an ion channel, but also a regulator of ENaC. Hyperactivation of ENaC entails increased channel opening time and/or modulation of the total number of channels in the epithelium [18, 28], leading to increased Na^+ and water resorption [17]. In addition, other extrinsic factors found at increased levels in CF, such as proteases (e.g. neutrophil elastase, cathepsin and some released by Gram-negative bacteria), or ENaC-specific mutations in atypical CF, can also activate ENaC [5]. Mutations in ENaC leading to reduced activity in patients who are also homozygous for the F508del mutation in *CFTR* have been associated with a long-term non-progressive CF phenotype, further implicating ENaC as a potential modifier of CF [29].

Despite this, and promising preclinical results, most ENaC inhibitors to date have been unsuccessful in clinical settings [30]. Target engagement of the inhibitor in the kidney, leading to hyperkalaemia, and unfavourable pharmacokinetics and pharmacodynamics of compound, are two common reasons [5]. It is also not clear whether ENaC inhibitors have been dosed adequately in previous studies [31].

The airway fluid absorption model in rats was used to calculate the BI 1265162 dose in humans. Unlike MCC, which is influenced by several other factors (e.g. ciliary beat frequency [32]), fluid absorption in the lung depends mainly on the activity of ENaC [17]. The MCC model is appropriate for the assessment of activity rather than comparison across compounds or dose calculations. In the rat model, BI 1265162 was intratracheally inserted into the lungs which ensured complete deposition of the test compound into the rat airways, whereas in the sheep model, this cannot be

ensured as the animals were nebulised. The ED_{70} of BI 1265162 was determined to be 0.18 µg/kg bodyweight in the rat. Extrapolated to a typical human of 75 kg, and with inhalation as a means of delivery, the expected dose to inhibit about 95% of ENaC in the airways is 200 µg.

BI 1265162 had no relevant effect on rat serum aldosterone at the doses tested in the study, suggesting that kidney function was not affected. Similarly, in sheep, BI 1265162 administered via inhalation increased whole-lung MCC without any relevant changes in plasma potassium after 24 hours, indicating no inhibition of kidney ENaC at the doses required for lung effects.

We have shown that BI 1265162 is highly potent in inhibiting Na^+ transport in a dose-dependent manner with IC_{50} of $3x10^{-9}$ M in the M1 mouse cell line and $8x10^{-9}$ M in the NCI-H441 human bronchial epithelial cell line. IC_{50} of amiloride in our study was $2.10x10^{-7}$ M and $2.38x10^{-7}$ M in M1 cells and NCI-H441 cells, respectively, indicating 30–70-fold higher potency of BI 1265162 compared with amiloride. Na^+ inhibition by BI 1265162 reduced water transport by 76% in M1 cells compared with saline control.

MCC regulation is a complex, multi-component system involving at least three major processes: ion and water transport; mucin synthesis and secretion; and CBF and ciliary coordination [32]. Via inhibition of ENaC, BI 1265162 increased MCC by 19% in the sheep model compared with vehicle. In a study in adult female sheep by Åstrand et al., nebulised isotonic (0.9%) saline did not increase MCC [33]. In a similar study by Coote et al., hypertonic (7%) saline had only limited efficacy [26]. Both nebulised isotonic and hypertonic saline are commonly used by CF patients to promote hydration of the airways. In our study, BI 1265162 significantly increased

MCC in female adult sheep, thereby demonstrating the potential of BI 1265162 as an inhaled therapy with superior efficacy in promoting MCC. BI 1265162-mediated improvement in MCC was also seen in human CF epithelium culture. The increase in MCC indicates restoration of the depleted fluid layer on the apical surface of the CF epithelia.

The MucilAir™ system used in this study is a 3D model of human epithelium reconstituted from primary human bronchial cells. It demonstrates the full functionality of the epithelial tissue when cultured on semi-porous membrane, and therefore provides a suitable model to test ENaC inhibitors in healthy and CF cells. Using this system, we found that in cells from a CF donor treated with IVA/LUM (an approved drug combination for treatment of CF), maximal MCC was 68% lower than that of a healthy donor. Concomitant BI 1265162 treatment restored MCC to the same levels as healthy epithelium, indicating possible synergistic effect between ENaC inhibition and CFTR modulation. It has been hypothesised that ion channels such as CFTR are passive and only move Cl^- according to the electrochemical gradient. Inhibition of ENaC can cause apical membrane hyperpolarisation, thereby having a CFTR-activating effect, creating an electrical driving force to induce Cl^- secretion into ASL [5]. *In vitro* studies have reported decreased activity of ENaC with IVA, indicating inhibitory effect of the drug on ENaC and possible synergism between CFTR modulation and ENaC inhibition [34]. Further work is needed to elaborate the effects of ENaC inhibition on CFTR channels in CF, either rescued by CFTR modulators or not. In addition, investigating the effects of ENaC inhibition on other mutant CFTR channels (e.g. G551D), either rescued or non-rescued, in human airway epithelial cells would be an interesting future study.

This study has some limitations. Cytotoxic effects of BI 1265162 at the concentrations assessed were not directly investigated in experiments measuring blockade of sodium absorption in M1 and H441 cell lines. However, cytotoxicity has been assessed during independent experiments using a human bronchial epithelial cell line, a human monocytic cell line and rat hepatocytes, with EC_{50}s >800 µM. The resorption of an instilled liquid load from rat lung has been used as readout for ENaC modulators previously [21]. We employed this method in examining the effect of BI 1265162 on airway fluid absorption in our rat model; however, we measured lung weight to determine fluid resorption whereas the previously published study employed magnetic resonance imaging. In our sheep model of MCC, experiments were carried out in two sheep per BI 1265162 dose and per vehicle; in previous studies of ENaC inhibitors in sheep, numbers of animals per treatment group ranged from two to five [18, 26, 33, 35]. Rat and sheep models do not exhibit airway mucous plugging and structural lung damage common in patients with CF, and instilled or inhaled ENaC inhibitor doses demonstrating positive results in these models may not achieve similar results in CF patients. However, these models are established, validated and widely used in studies of CF therapies. Finally, our experiments investigating the effect of BI 1265162 on fluid transport and MCC in non-CF and CF air–liquid interface cultures are based on bronchial cells provided by single donors. In addition, we did not analyse apical fluid electrolyte composition, and the determination of fluid transport by weighing Transwell® inserts in these experiments, as compared with measurements of fluid height, is an uncommon methodology.

Conclusion

BI 1265162 shows promising results as an inhibitor of ENaC, both *in vitro* and *in vivo*. The compound effectively inhibited Na^+ transport leading to reduction in water

resorption in cell lines and rat models, and accelerated MCC in a sheep model without effect on renal function. In normal and CF human epithelial models, BI 1265162 decreased apical to basal water transport, and increased MCC alone and in combination with CFTR modulation. BI 1265162 allowed IVA/LUM in CF epithelium to reach MCC levels seen in normal epithelium, suggesting a possible synergistic effect. Taken together, these preclinical results demonstrate the potential of BI 1265162 as an ENaC inhibitor-based therapy for respiratory effects of CF. The benefit could lie with treatment with ENaC inhibition alone or in combination, additively, with CFTR modulators, and be mutation agnostic.

Acknowledgements

The authors would like to thank Kerstin Benediktus, Madlen Hahn, Gabriele Göggerle, Julia Wolf, Almut Schüle, Mathilde Borsch and Angelika Hoffmann for their excellent technical assistance during the conduct of these studies.

Funding

This work was supported by Boehringer Ingelheim International GmbH. Medical writing assistance, in the form of the preparation and revision of the manuscript, was supported financially by Boehringer Ingelheim, and provided by Lee Kempster and Ishmam Nawar of MediTech Media (London, UK) under the authors' conceptual direction and based on feedback from the authors.

Conflicts of interest

PN and AG are employees of Boehringer Ingelheim. BJ was an employee of Boehringer Ingelheim at the time of study. JS and SC report grants from Boehringer Ingelheim at the time of study.

References

1. Ratjen F, Bell SC, Rowe SM, Goss CH, Quittner AL, Bush A. Cystic fibrosis. *Nat Rev Dis Primers* 2015; **1**: 15010.
2. Knowles MR, Boucher RC. Mucus clearance as a primary innate defense mechanism for mammalian airways. *J Clin Invest* 2002; **109**: 571-577.
3. Mall M, Bleich M, Greger R, Schreiber R, Kunzelmann K. The amiloride-inhibitable Na+ conductance is reduced by the cystic fibrosis transmembrane conductance regulator in normal but not in cystic fibrosis airways. *J Clin Invest* 1998; **102**: 15-21.
4. Althaus M. ENaC inhibitors and airway re-hydration in cystic fibrosis: state of the art. *Curr Mol Pharmacol* 2013; **6**: 3-12.
5. Moore PJ, Tarran R. The epithelial sodium channel (ENaC) as a therapeutic target for cystic fibrosis lung disease. *Expert Opin Ther Targets* 2018; **22**: 687-701.
6. Hill DB, Long RF, Kissner WJ, Atieh E, Garbarine IC, Markovetz MR, Fontana NC, Christy M, Habibpour M, Tarran R, Forest MG, Boucher RC, Button B. Pathological mucus and impaired mucus clearance in cystic fibrosis patients result from increased concentration, not altered pH. *Eur Respir J* 2018; **52**: pii: 1801297.
7. Ponzano S, Nigrelli G, Fregonese L, Eichler I, Bertozzi F, Bandiera T, Galietta LJV, Papaluca M. A European regulatory perspective on cystic fibrosis: current treatments, trends in drug development and translational challenges for CFTR modulators. *Eur Respir Rev* 2018; **27**: 170124.
8. Edmondson C, Davies JC. Current and future treatment options for cystic fibrosis lung disease: latest evidence and clinical implications. *Ther Adv Chronic Dis* 2016; **7**: 170-183.
9. Heijerman HGM, McKone EF, Downey DG, Van Braeckel E, Rowe SM, Tullis E, Mall MA, Welter JJ, Ramsey BW, McKee CM, Marigowda G, Moskowitz SM, Waltz D, Sosnay PR, Simard C, Ahluwalia N, Xuan F, Zhang Y, Taylor-Cousar JL, McCoy KS, McCoy K, Donaldson S, Walker S, Chmiel J, Rubenstein R, Froh DK, Neuringer I, Jain M, Moffett K, Taylor-Cousar JL, Barnett B, Mueller G, Flume P, Livingston F, Mehdi N, Teneback C, Welter J, Jain R, Kissner D, Patel K, Calimano FJ, Johannes J, Daines C, Keens T, Scher H, Chittivelu S, Reddivalam S, Klingsberg RC, Johnson LG, Verhulst S, Macedo P, Downey D, Connett G, Nash E, Withers N, Lee T, Bakker M, Heijerman H, Vermeulen F, Van Braeckel E, Knoop C, De Wachter E, van der Meer R, Merkus P, Majoor C. Efficacy and safety of the elexacaftor plus tezacaftor plus ivacaftor combination regimen in people with cystic fibrosis homozygous for the *F508del* mutation: a double-blind, randomised, phase 3 trial. *Lancet* 2019; **394**: 1940-1948.
10. Middleton PG, Mall MA, Dřevínek P, Lands LC, McKone EF, Polineni D, Ramsey BW, Taylor-Cousar JL, Tullis E, Vermeulen F, Marigowda G, McKee CM, Moskowitz SM, Nair N, Savage J, Simard C, Tian S, Waltz D, Xuan F, Rowe SM, Jain R. Elexacaftor–tezacaftor–ivacaftor for cystic fibrosis with a single Phe508del allele. *N Engl J Med* 2019; **381**: 1809-1819.
11. Cystic Fibrosis Mutation Database. Home page. http://genet.sickkids.on.ca/Home.html. Date last accessed: November 4 2019.
12. Cystic Fibrosis Foundation. Types of CFTR mutations. https://www.cff.org/What-is-CF/Genetics/Types-of-CFTR-Mutations/. Date last accessed: November 4 2019.

13. Couroux P, Farias P, Rizvi L, Griffin K, Hudson C, Crowder T, Tarran R, Tullis E. First clinical trials of novel ENaC targeting therapy, SPX-101, in healthy volunteers and adults with cystic fibrosis. *Pulm Pharmacol Ther* 2019; **58**: 101819.
14. Skilton M, Krishan A, Patel S, Sinha IP, Southern KW. Potentiators (specific therapies for class III and IV mutations) for cystic fibrosis. *Cochrane Database Syst Rev* 2019: CD009841.
15. Khoury O, Barrios C, Ortega V, Atala A, Murphy SV. Immunomodulatory cell therapy to target cystic fibrosis inflammation. *Am J Respir Cell Mol Biol* 2018; **58**: 12-20.
16. Shei R-J, Peabody JE, Kaza N, Rowe SM. The epithelial sodium channel (ENaC) as a therapeutic target for cystic fibrosis. *Curr Opin Pharmacol* 2018; **43**: 152-165.
17. Mall MA, Galietta LJV. Targeting ion channels in cystic fibrosis. *J Cyst Fibros* 2015; **14**: 561-570.
18. Scott DW, Walker MP, Sesma J, Wu B, Stuhlmiller TJ, Sabater JR, Abraham WM, Crowder TM, Christensen DJ, Tarran R. SPX-101 is a novel epithelial sodium channel–targeted therapeutic for cystic fibrosis that restores mucus transport. *Am J Respir Crit Care Med* 2017; **196**: 734-744.
19. Clunes MT, Boucher RC. Cystic fibrosis: The mechanisms of pathogenesis of an inherited lung disorder. *Drug Discov Today Dis Mech* 2007; **4**: 63-72.
20. Berdiev BK, Qadri YJ, Benos DJ. Assessment of the CFTR and ENaC association. *Mol Biosyst* 2009; **5**: 123-127.
21. Blé FX, Cannet C, Collingwood S, Danahay H, Beckmann N. ENaC-mediated effects assessed by MRI in a rat model of hypertonic saline-induced lung hydration. *Br J Pharmacol* 2010; **160**: 1008-1015.
22. Dhand R, Eicher J, Hansel M, Jost I, Meisenheimer M, Wachtel H. Improving usability and maintaining performance: human-factor and aerosol-performance studies evaluating the new reusable Respimat inhaler. *Int J Chron Obstruct Pulmon Dis* 2019; **14**: 509-523.
23. Güney Ş, Schuler A, Ott A, Höschele S, Zügel S, Baloğlu E, Bärtsch P, Mairbäurl H. Dexamethasone prevents transport inhibition by hypoxia in rat lung and alveolar epithelial cells by stimulating activity and expression of Na+-K+-ATPase and epithelial Na+ channels. *Am J Physiol Lung Cell Mol Physiol* 2007; **293**: L1332-L1338.
24. Gondzik V, Awayda MS. Methods for stable recording of short-circuit current in a Na+-transporting epithelium. *Am J Physiol Cell Physiol* 2011; **301**: C162-C170.
25. Blouquit S, Morel H, Hinnrasky J, Naline E, Puchelle E, Chinet T. Characterization of ion and fluid transport in human bronchioles. *Am J Respir Cell Mol Biol* 2002; **27**: 503-510.
26. Coote KJ, Paisley D, Czarnecki S, Tweed M, Watson H, Young A, Sugar R, Vyas M, Smith NJ, Baettig U. NVP-QBE 170: an inhaled blocker of the epithelial sodium channel with a reduced potential to induce hyperkalaemia. *Br J Pharmacol* 2015; **172**: 2814-2826.
27. Taouil K, Hinnrasky J, Hologne C, Corlieu P, Klossek J-M, Puchelle E. Stimulation of β2-adrenergic receptor increases cystic fibrosis transmembrane conductance regulator expression in human airway epithelial cells through a cAMP/protein kinase A-independent pathway. *J Biol Chem* 2003; **278**: 17320-17327.
28. Thibodeau PH, Butterworth MB. Proteases, cystic fibrosis and the epithelial sodium channel (ENaC). *Cell Tissue Res* 2013; **351**: 309-323.

29. Agrawal PB, Wang R, Li HL, Schmitz-Abe K, Simone-Roach C, Chen J, Shi J, Louie T, Sheng S, Towne MC, Brainson CF, Matthay MA, Kim CF, Bamshad M, Emond MJ, Gerard NP, Kleyman TR, Gerard C. The epithelial sodium channel is a modifier of the long-term nonprogressive phenotype associated with F508del CFTR mutations. *Am J Respir Cell Mol Biol* 2017; **57**: 711-720.
30. Cystic Fibrosis Foundation. Drug development pipeline. https://www.cff.org/Trials/pipeline. Date last accessed: January 8 2020.
31. Danahay H, McCarthy C, Abraham W, Charlton H, Lilley Sarah, Fox R, Gosling M. 210 - Pharmacokinetic and pharmacodynamic profile of a novel inhaled enac blocker, ETD001. In: 32nd Annual North American Cystic Fibrosis Conference (NACFC); 2018 October 18-20; Denver, CO, USA; 2018.
32. Sears PR, Yin W-N, Ostrowski LE. Continuous mucociliary transport by primary human airway epithelial cells in vitro. *American Journal of Physiology-Lung Cellular and Molecular Physiology* 2015; **309**: L99-L108.
33. Astrand AB, Hemmerling M, Root J, Wingren C, Pesic J, Johansson E, Garland AL, Ghosh A, Tarran R. Linking increased airway hydration, ciliary beating, and mucociliary clearance through ENaC inhibition. *Am J Physiol Lung Cell Mol Physiol* 2015; **308**: L22-32.
34. Cholon DM, Esther CR, Jr., Gentzsch M. Efficacy of lumacaftor-ivacaftor for the treatment of cystic fibrosis patients homozygous for the F508del-CFTR mutation. *Expert Review of Precision Medicine and Drug Development* 2016; **1**: 235-243.
35. Terryah ST, Fellner RC, Ahmad S, Moore PJ, Reidel B, Sesma JI, Kim CS, Garland AL, Scott DW, Sabater JR. Evaluation of a SPLUNC1-derived peptide for the treatment of cystic fibrosis lung disease. *American Journal of Physiology-Lung Cellular and Molecular Physiology* 2017; **314**: L192-L205.

Figure Legends

Figure 1. Concentration–response curves and IC_{50} values for BI 1265162 in NCI-H441 cells

Inhibition of Na^+ transport by BI 1265162 was tested in M1 and NCI-H441 cells. Cells were cultivated on polyester Transwell® filters to electrically tight monolayers. Filters containing cell layers were inserted into an Ussing chamber and short-circuit current (I_{SC}) measured at increasing BI 1265162 final concentrations. I_{SC} was compared against maximum inhibition with amiloride and inhibition concentration that reduced the effect by 50% (IC_{50}) calculated.

IC_{50}, inhibition concentration that reduced the effect by 50%; M1, mouse renal collecting duct cell line.

Figure 2. Inhibition of water resorption by BI 1265162 in M1 cell line

Cells were cultivated on polyester Transwell® filters to electrically tight monolayers. Apical liquid volume replaced with either saline control or saline containing 3 µM BI 1265162. Tritiated water was then added and mixed with the apical volume of the Transwell®, and water resorption measured by scintigraphy using a radiometric dilution assay.

**** P<0.0001, unpaired t-test. SEM, standard error of mean.

Figure 3. Inhibition of lung fluid absorption by BI 1265162 in rats

Ringer Lactate Solution pH 5 alone or with increasing concentrations of BI 1265162 was instilled into the lungs of male Wistar rats. Three hours after instillation, animals were sacrificed and the weight of the lungs was determined. Inhibition of liquid transport was calculated from lung weights in the treated group versus lung weights of a negative control group, and an untreated control group was used as reference.

Data shown ± standard error of the mean. **** P<0.0001, one-way ANOVA, Dunnett's multiple comparison test.

Figure 4: Effect of BI 1265162 on (a) retention of tracer in lung of sheep and (b) K^+ concentration in sheep; n=2 per dose.

Adult ewes were administered varying doses of BI 1265162 or vehicle using an AirLife™ nebuliser. Mucociliary clearance was measured by administration of aerosolised technetium-labelled sulphur colloid followed by gamma scintigraphy. Serial images were obtained over a 2-hour period and counts were obtained from the right lung. Blood was collected and plasma potassium was determined to assess renal effects of BI 1265162.

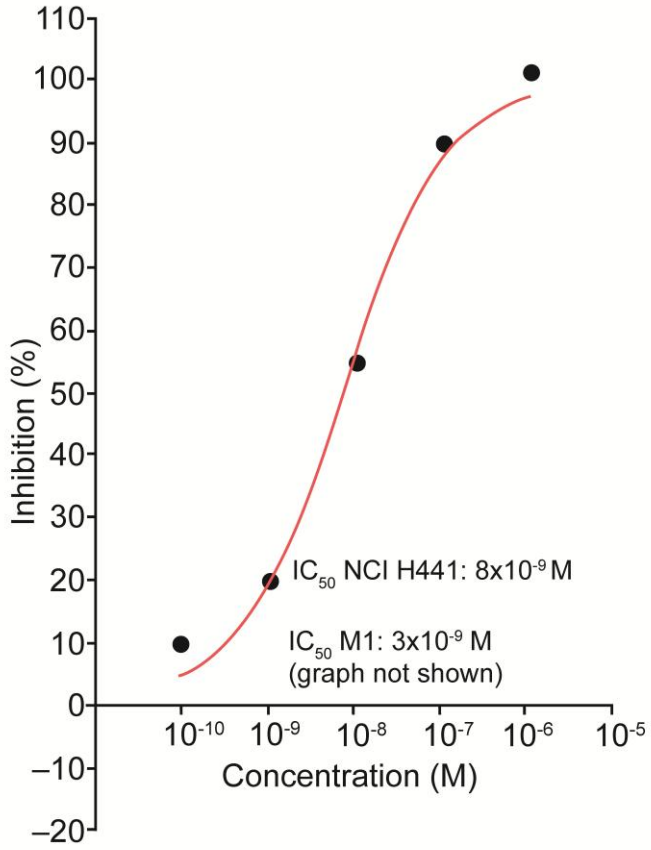
Data show mean ± range. * P=0.0027 and 0.0003 at 2 hours after radiolabel administration, vehicle versus 1 µg/kg and 10 µg/kg, respectively. One-way ANOVA.

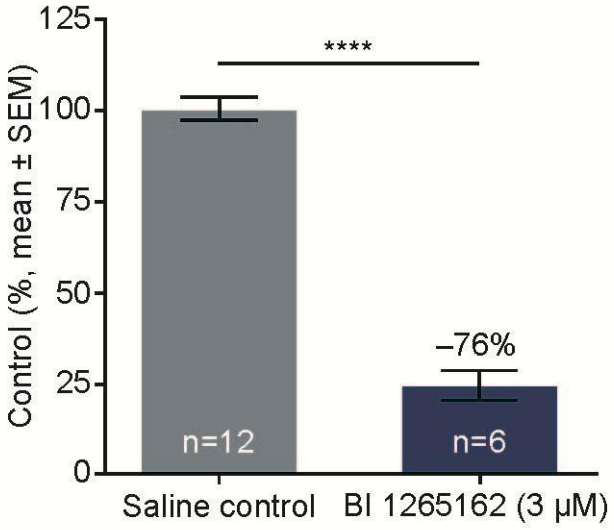
Figure 5: Effect of BI 1265162 on water transport and MCC in normal and cystic fibrosis MucilAir™ cultures

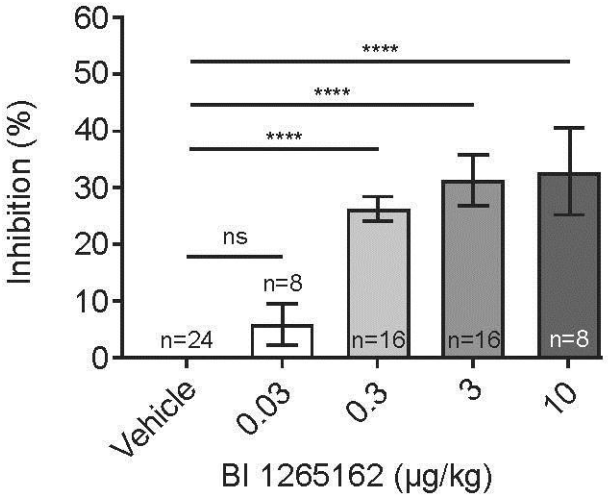
The effect of BI 1265162, with or without CFTR modulators and isoproterenol (an upregulator of CFTR expression) on water transport and MCC was evaluated in a pseudostratified, fully differentiated 3D model of human epithelium (n=5 cultures per treatment) employing bronchial cells from a CF and a non-CF donor. Water transport was measured on Days 2 and 5 of the study by weighing the membrane inserts containing the cells. MCC was measured on Day 7 by video-tracking the movements of polystyrene microbeads added to the apical surface of MucilAir™.

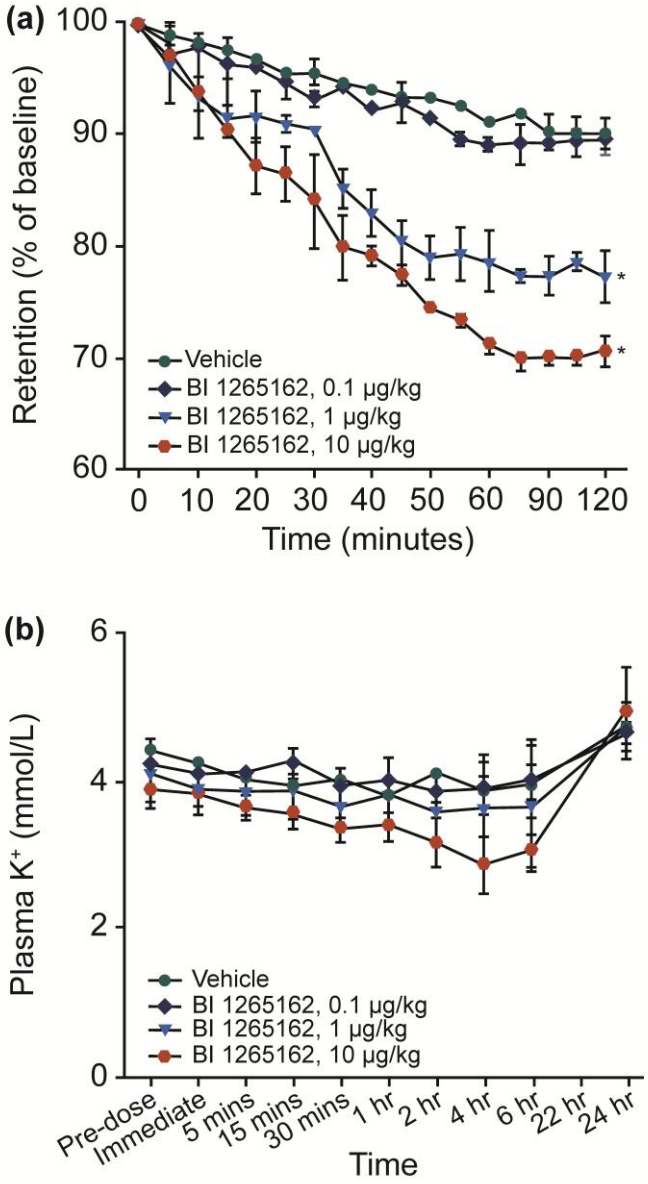
Error bars show standard error of mean. * P<0.05, ** P<0.01, *** P<0.001, **** P<0.0001 vehicle versus BI 1265162.

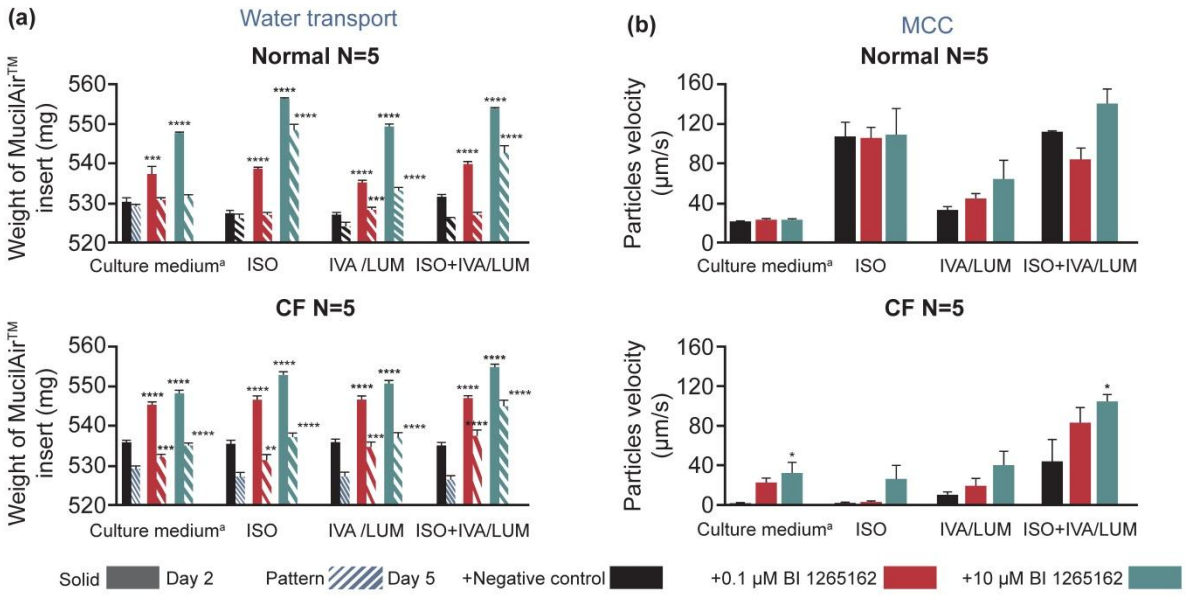
CF, cystic fibrosis; MCC, mucociliary clearance; ISO, isoproterenol; IVA/LUM, ivacaftor/lumacaftor.


110
100
90
80
70
60
50
40
30
20
10
0
–10
–20
Inhibition (%)
IC50 NCI H441: 8x10-9 M
IC50 M1: 3x10-9 M
(graph not shown)
10-10
10-9
10-8
10-7
10-6
10-5
Concentration (M)


125
100
75
50
25
0
Control (%, mean ± SEM)
****
–76%
n=12
n=6
Saline control
BI 1265162 (3 µM)


60
50
40
30
20
10
0
Inhibition (%)
****
****
****
ns
n=8
n=24
n=16
n=16
n=8
Vehicle
0.03
0.3
3
10
BI 1265162 (µg/kg)
0
-18
45
18
18
% increase in aldosterone


(a)
Retention (% of baseline)
100
90
80
70
60
0 10 20 30 40 50 60 90 120
Time (minutes)
Vehicle
BI 1265162, 0.1 µg/kg
BI 1265162, 1 µg/kg
BI 1265162, 10 µg/kg
*
*
(b)
Plasma K+ (mmol/L)
6
4
2
0
Pre-dose
Immediate
5 mins
15 mins
30 mins
1 hr
2 hr
4 hr
6 hr
22 hr
24 hr
Time
Vehicle
BI 1265162, 0.1 µg/kg
BI 1265162, 1 µg/kg
BI 1265162, 10 µg/kg


(a)
Water transport
Normal N=5
Weight of MucilAir™ insert (mg)
560
550
540
530
520
Culture medium[a]
ISO
IVA /LUM
ISO+IVA/LUM
CF N=5
(b)
MCC
Normal N=5
Particles velocity (µm/s)
160
120
80
40
0
IVA/LUM
CF N=5
Solid
Day 2
Pattern
Day 5
+Negative control
+0.1 µM BI 1265162
+10 µM BI 1265162

Preclinical evaluation of the ENaC inhibitor BI 1265162 for treatment of cystic fibrosis

Peter Nickolaus PhD[1], Birgit Jung MD[1], Juan Sabater MD[2], Samuel Constant PhD[3], Abhya Gupta MD[1]

[1]Boehringer Ingelheim Pharma GmbH & Co.KG, Biberach, Germany; [2]Mount Sinai Medical Center, Miami Beach, Florida, USA; [3]Epithelix Sàrl, Plan-les-Ouates, Switzerland.

Online Supporting Information

Methods

In vitro inhibition of Na^+ transport

The inhibition of Na^+ transport by BI 1265162 was tested in a mouse renal collecting duct cell line (M1) and a human bronchial epithelial cell line (NCI-H441) using a custom-made Ussing chamber.

M1 cells were cultivated in Dulbecco's Modified Eagle Medium, containing 5% foetal calf serum (FCS) and 5 µM dexamethasone for 10–12 days on polyester Transwell® filters. NCI-H441 cells were cultivated in RPMI1640 containing 10% FCS, 1% sodium pyruvate and 5 mL insulin/transferring/selenium on polyester Transwell® filters at 37°C, 5% CO_2 and 95% humidity. After 2 days, the basolateral bath solution was replaced with culture media containing 200 nM dexamethasone. The apical bath solution was removed to create an air–liquid interface. Dexamethasone was used in both cell lines to upregulate ENaC expression and to achieve sufficient short circuit current ($I_{SC;}$ a measure of net ion transport).[1]

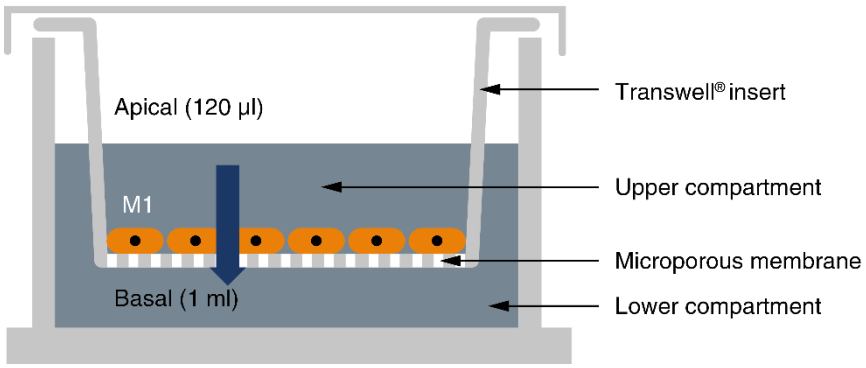
Filters containing cell layers were inserted into a Teflon-coated well plate, which fitted into the Ussing chamber. The amount of the transported Na^+ was measured by the application of the I_{SC} that was necessary to bring the measurable voltage difference down to 0 mV.[2] I_{SC} was measured in the voltage clamp mode using a custom-built amplifier (Boehringer Ingelheim, Biberach, Germany), with the software package Lab View used for data acquisition and analysis. Every cell filter was used as its own control. Measurements were only conducted if a minimum transepithelial electrical resistance of 800 Ω or 250 Ω, and an I_{SC} of 1.7 microampere (µA), or between 8 and 17 µA, were reached (dependent on cell type; for M1 and NCI-H441, respectively).

BI 1265162 (Boehringer Ingelheim GmbH & Co.KG, Biberach, Germany) was administered in a stepwise manner at final concentrations of 10^{-10}, 10^{-9}, 10^{-8}, 10^{-7} and 10^{-6} M to the apical solution of each filter. At the end of each experiment, I_{SC} was measured by adding $3x10^{-6}$ M amiloride, an inhibitor of transepithelial Na^+ transport,[3] to the apical compartment of each filter. Differences in I_{SC} after addition of test compounds were compared with the amiloride effect (maximum inhibition). Results were expressed as inhibition in percent of the amiloride effect, and the inhibition concentration that reduced the effect by 50% (IC_{50}) was calculated by the GraphPad Prism software package (GraphPad Prism for Windows, version 5).

In vitro inhibition of water resorption

ENaC-mediated water transport with and without BI 1265162 was measured using a Transwell® system. M1 cells (5,000 cells/well) were grown in a monolayer on microporous membranes suspended in Lonza PC-1 medium in a Costar 3470 Transwell® plate (E-Figure 1). Experiments were carried out in duplicate.

E-Figure 1: Set-up of the Transwell® system



To assure a tight diffusion barrier on Day 10 after seeding, the resistance between the apical and basolateral compartment divided by the cell layer was measured using a voltmeter. Inserts containing cells showing a resistance between 2,200-2,800 Ω were used for measurements.

PC-1 medium (500 µL per well) was added into an assay plate (Costar 3524, basolateral) and equilibrated for 2 hours in a humidified incubator at 37°C, 5% CO_2. The membranes containing M1 cells were put into the assay plate and the apical liquid volume from the M1 cell layers was carefully aspirated. 3 µM BI 1265162 in 120 µL of saline (n=3 replicates for each experiment) or saline alone was added apically. The assay plate was stored for 24 hours in a humidified incubator at 37°C, 5% CO_2.

In order to seal the membrane after the 24-hour incubation, each insert was placed into a Petri dish with silicon paste. Since the volume differences measured in this in vitro assay were very small, a radiometric dilution assay was employed. For determination of volume of water on the apical side, 80 µL of diluted ^3H water (Hartmann Analytics, Braunschweig, Germany) was added and mixed with the apical

volume of the Transwell®; 80 µL of this mixture was transferred into a scintillation vial. In parallel, the entire apical volume was transferred directly without mixing into six scintillation vials (measurement of whole activity). 3.5 mL Ultima Gold scintillation solution (Perkin Elmer) was added to each vial, vortexed and the amount of radioactivity (disintegration per minute [dpm]) was measured. Unpaired t-test was carried out and the values $P<0.05$ were nominally considered statistically significant.

In vivo inhibition of liquid resorption

Efficacy of BI 1265162 on inhibition of liquid absorption from the airway epithelium of male Wistar rats was assessed. Animal studies were performed according to the German Animal Welfare Regulations and approved by the Tübingen Regional Administrative Council, licence 12-009.

Rats weighing 260–340 g were randomly assigned to the control and treatment groups (n=8 per group). The animals were anaesthetised with isoflurane prior to intratracheal instillation of test compound or vehicle. For the treatment groups, Ringer Lactate Solution pH 5 (vehicle) alone or with BI 1265162 was instilled in a volume of 5 mL/kg. The following concentrations of BI 1265162 were tested: 10, 3, 0.3 and 0.03 µg/kg of body weight. After this, animals were awake again; three hours after instillation, they were re-anaesthetised once more and blood was withdrawn to obtain serum. Aldosterone was determined via ELISA (Aldosterone ELISA, BIOTREND) from serum. The animals were sacrificed under anaesthesia by cervical dislocation. Lungs were removed, non-pulmonary tissue was dissected, and the weight of the lung was determined. To calculate the inhibition of liquid transport in the current set-up, historical data of lung weights of a negative control group (treated only with 5 mL/kg Ringer Lactate Solution before weighing) and an untreated control

group were used as reference. The variable ‘inhibition’ used for statistical analysis was calculated from the lung weight using the following equation:

$$y_{inh} = 1 - \left(\frac{1 - \left(\frac{y_i - \bar{y}_u}{\bar{y}_{neg} - \bar{y}_u} \right)}{1/n_p \sum_{j=1}^{n_p} \left(1 - \left(\frac{y_{j,p} - \bar{y}_u}{\bar{y}_{neg} - \bar{y}_u} \right) \right)} \right) * 100$$

where y_{inh} = inhibition [%],

y_i = lung weight of each animal i,

$\bar{y}_u$ = mean lung weight of the untreated (historical) control group,

$\bar{y}_{neg}$ = mean lung weight of the negative (historical) control group,

n_p = number of animals in the placebo (day control) group,

$y_{j,p}$ = lung weight of each animal j in the placebo (day control) group.

The mean lung weight of the historical control groups was measured separately for each experiment. Each treatment group had its own historical control group assigned according to historical body weight. The animals of the historical control groups were chosen by the smallest and highest body weight value of the respective experimental groups. Data from all experiments, carried out on three separate occasions, were combined to estimate the dose-response curve. Effective doses at 50, 70 and 90% of the maximum effect of BI 1265162 were estimated by means of non-linear regression.

Acceleration of MCC in a sheep model

Stimulation of MCC by BI 1265162 (0.1, 1.0, and 10 µg/kg) was tested in a sheep model of whole-lung clearance measuring the retention of a radioactive tracer over 2 hours.

The studies were conducted at Mount Sinai Medical Center (Miami, FL, USA) after approval from the Mount Sinai Medical Center Animal Research Committee.

Adult ewes (25–45 kg, Florida Native; 1–4 years old; Fair Meadows Farm, Ocala, FL, USA) were anaesthetised by local application of lidocaine prior to nasal intubation via bronchoscope, then administered a total of 3 mL (varying compound doses with n=2 in each dose group) using an AirLife™ nebuliser. The animals received the compound or vehicle (deionised water). Aerosolized technetium-labelled sulphur colloid (99mTc-SC; 20 mCi) was administered to measure the effects of the various doses of test compounds or control on MCC by gamma scintigraphy as previously described.[4] Administration of 99mTc-SC occurred at the stated times following administration of drug or control. Serial images were then obtained over a 1-hour period at 5-minute intervals for the first hour and then every 15 minutes for the next hour. Counts from the right lung were corrected for decay and expressed as a percentage of radioactivity cleared relative to the baseline image (% cleared).

Retention of radioactive tracer to determine MCC and plasma potassium levels were expressed as mean ± range. A one-way analysis of variance (ANOVA) was performed on the retention values at 1 hour and 2 hours after radiolabel delivery, versus vehicle control.

Blood was collected and plasma potassium determined. Plasma potassium levels were analysed across time for each dose using a one-way ANOVA.

In vitro effect on water transport and MCC on CF donor cells

The effect of BI 1265162, with or without ivacaftor (IVA; CFTR corrector) and lumacaftor (LUM; CFTR potentiator) and isoproterenol (ISO) (which, as a non-selective β-adrenoreceptor agonist, upregulates CFTR expression) on water

transport, MCC and ciliary beat frequency (CBF) was evaluated using MucilAir™. This is a fully differentiated, pseudostratified 3D model of human epithelium, reconstituted in vitro from either primary human bronchial cells isolated from a donor without CF (MucilAir™) or from a CF donor (ΔF508/homozygous, MucilAir™-CF). MucilAir™/-CF demonstrates the full functionality of the epithelial tissue when cultured on semi-porous membrane. Experiments were carried out on n=5 cultures per treatment.

Proprietary culture medium containing 50 µL BI 1265162 (0.1 and 10 µM) was applied on the apical surface of MucilAir™ and MucilAir™-CF, with 0.1 µM IVA / 3 µM LUM and with or without 100 µM ISO in the basolateral compartment.

Water transport was measured on Days 2 and 5 of the study by weighing the semi-porous membrane inserts containing the cells.

MCC was measured on Day 7 by using a Sony XCD-U100CR camera connected to an Olympus BX51 microscope with a 5x objective. Polystyrene microbeads (30 µM in diameter) were added on the apical surface of MucilAir™ and movements were video-tracked at two frames per second for 30 images at room temperature. Three movies were taken per insert. Average beads movement velocity (µM/sec) was calculated with the ImageProPlus 6.0 software. Data were expressed as mean ± standard error of the mean. Differences, induced by treatments, were tested by a one-way or two-way ANOVA using Prism 6 GraphPad software (La Jolla, CA, USA). Dunnett's multiple comparison post-tests were used to compare every mean to control mean (vehicle) for each series of conditions. The values $P<0.05$ were nominally considered statistically significant.

References

1. Güney Ş, Schuler A, Ott A, et al. Dexamethasone prevents transport inhibition by hypoxia in rat lung and alveolar epithelial cells by stimulating activity and expression of Na+-K+-ATPase and epithelial Na+ channels. *American Journal of Physiology-Lung Cellular and Molecular Physiology.* 2007;293(5):L1332-L1338.
2. Gondzik V, Awayda MS. Methods for stable recording of short-circuit current in a Na+-transporting epithelium. *American Journal of Physiology-Cell Physiology.* 2011;301(1):C162-C170.
3. Blouquit S, Morel H, Hinnrasky J, Naline E, Puchelle E, Chinet T. Characterization of ion and fluid transport in human bronchioles. *American Journal of Respiratory Cell and Molecular Biology.* 2002;27(4):503-510.
4. Coote KJ, Paisley D, Czarnecki S, et al. NVP-QBE 170: an inhaled blocker of the epithelial sodium channel with a reduced potential to induce hyperkalaemia. *British Journal of Pharmacology.* 2015;172(11):2814-2826.