2012-04-24

Lack of CFTR in CD3+ Lymphocytes Leads to Aberrant Cytokine Secretion and Hyper-Inflammatory Adaptive Immune Responses: A Master's Thesis

Christian Mueller
University of Massachusetts Medical School

LACK OF CFTR IN CD3+ LYMPHOCYTES LEADS TO ABERRANT CYTOKINE SECRETION AND HYPER-INFLAMMATORY ADAPTIVE IMMUNE RESPONSES

A Master's Thesis Presented

By

Christian Mueller

Submitted to the Faculty of the

University of Massachusetts Graduate School of Biomedical Sciences, Worcester
In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

April 24, 2012

Masters in Clinical Investigation

LACK OF CFTR IN CD3+ LYMPHOCYTES LEADS TO ABERRANT CYTOKINE SECRETION AND HYPER-INFLAMMATORY ADAPTIVE IMMUNE RESPONSES

A Master's Thesis Presented

By

Christian Mueller

The signature of the Master's Thesis Committee signify completion and approval as to style and content of the Thesis

Katherine Luzuriaga, Chair of the Committee

Miguel Esteves, Member of the Committee

Guangping Gao, Member of the Committee

The signature of the Dean of the Graduate School of Biomedical Sciences signifies that the student has met all master's degree graduation requirements of the school.

Anthony Carruthers, Ph.D,
Dean of the Graduate School of Biomedical Sciences

Masters in Clinical Investigation

April 24 2012

Acknowledgments

I would like to acknowledge the grant support from NHLBI (HL69877) the Cystic Fibrosis Foundation, the Alpha-1 Antitrypsin Foundation, and the fellowship from the Parker B. Francis Foundation.

Abstract

Background: Cystic fibrosis (CF) remains the most common fatal monogenic disease in the US, affecting 1 in 3,300 live births. CF is the result of mutations in CFTR, a chloride channel and regulator of other ion channels.The mechanisms by which CFTR mutations cause chronic lung disease in CF are not fully defined, but may include the combined effects of altered ion and water transport across the airway epithelium and aberrant inflammatory and immune responses to pathogens within the airways. We have shown that Cftr-/- mice mount an exaggerated IgE response towards Aspergillus fumigatus (Af) when compared to Cftr+/+ mice. Along with the increased IgE levels, the Cftr-/- mice had higher levels of IL-13 and IL-4, mimicking both the Th-2 biased immune responses and predilection to mounting Af-specifc IgE seen in CF patients. Herein we hypothesize that these immune aberrations are primarily due to the lack of Cftr expression in lymphocytes rather than with Cftr deficiency in the epithelium. *Results:* Our results indicate that adoptive transfer experiments with Cf splenocytes confer higher IgE response to Af in host mice as compared to hosts receiving wild-type splenocytes. The predilection of Cftr-deficient lymphocytes to mount Th2 responses was confirmed by *in vitro* antigen recall experiments, where higher levels of IL-13 and IL-4 where seen only in the presence of Cftr-deficient lymphocytes. Conclusive data on this phenomenon were obtained with conditional Cftr knockout mice, where mice lacking Cftr in T-cell lineages developed the higher IgE titers as compared to their wild-type littermate controls.

Further analysis of Cftr-deficient lymphocytes revealed an enhanced intracellular Ca^{2+} flux in response to T cell receptor activation as compared to normal lymphocytes. This was accompanied by a significant increase in nuclear localization of the calcium-sensitive transcription factor NFAT, which could contribute to the enhanced secretion of IL-13 and other cytokines. *Conclusions*: In summary, our data identified that CFTR dysfunction in T cells can lead directly to aberrant immune responses. This is the first instance that a CF related phenotype has been entirely modeled in vivo by selectively knocking out CFTR in the immune system. Specifically, Cftr deficient lymphocytes directed skewed responses to *Aspergillus fumigatus,* leading to a higher than normal IgE response. These findings implicate the lymphocyte population as a potentially important target for therapeutics directed to the treatment of CF lung disease.

Table of Contents

List of Figures

Preface

The work and ideas presented in this thesis has resulted in the publication of the two manuscripts cited below.

1. **Mueller C**, Braag SA, Keeler A, Hodges C, Drumm M, Flotte TR. *Lack of Cftr in CD3+ Lymphocytes Leads to Aberrant Cytokine Secretion and Hyper-inflammatory Adaptive Immune Responses*. Am J Respir Cell Mol Biol. 2010 Aug 19.: PMID:20724552

2. Ratner D, **Mueller C**. Immune responses in Cystic Fibrosis; are they intrinsically defective? Am J Respir Cell Mol Biol. 2012 Mar 8. [Epub ahead of print] PMID: 22403802

CHAPTER I: Introduction

Cystic fibrosis (CF) is the most common autosomal recessive genetic disease in the US, affecting 1 in 3,300 live births. CFTR is a chloride channel and a regulator of other ion channels, and many aspects of the CF phenotype are directly related to ion channel abnormalities attributable to Cftr mutation. Initially, CF was described as a constellation of pancreatic pathology and recurrent lung infections, but it was soon realized that the clinical and pathological findings could be better explained as a generalized defect in all exocrine glands. The manifestation of abnormal exocrine gland function can be divided into three types: 1, those that become blocked by viscid or solid eosinophilic material in the lumen (i.e. pancreas, intestinal glands, intrahepatic bile ducts, gallbladder, submaxillary glands); 2, those glands that produce excess of secretions (i.e. tracheobronchial and Brunner glands); and 3, those glands that are histologically normal yet secrete excessive amounts of electrolytes (i.e., sweat, parotid, and small salivary glands) [1,2]. Lung disease is the most common limitation to the quantity and quality of life for CF patients. In prenatal life, the lung manifestations of CF are extremely subtle, although hyperplasia of submucosal glands has been reported. Postnatally, CF patients develop evidence of small airways obstruction and inflammation, most often beginning within the first two years of life. Patients typically develop airway infection with certain species of bacteria, often beginning with Staphylococcus aureus and typically progressing to infection with Pseudomonas aeruginosa[3-6]. Coincident with airway infection, an exuberant

inflammatory response occurs in the airways of CF patients. This response is dominated by neutrophil infiltration, although adaptive immune responses to the infecting organisms are typical as well. It is not entirely clear why CF patients are particularly prone to airway infection with P. aeruginosa and the other organisms mentioned above. The mechanisms by which CFTR mutations cause chronic lung disease in CF are not fully defined, but may include the combined effects of altered ion and water transport across the airway epithelium[7-9], increased binding or decreased clearance of Pseudomonas aeruginosa [10,11] as well as increased pro-inflammatory cytokine production in the CF airway [12-16]. CF cell lines demonstrate increased NFkappaB activation and increased IL-8 secretion in response to P. aeruginosa exposure, as compared with control cells [16,17]. Furthermore, CFTR mutant mice demonstrate a greater cytokine response (KC, MIP2, IL1-beta), greater mortality, and weight loss after airway challenge with a P. aeruginosa-agarose bead slurry, as compared with control mice [18-21].

Although it is not clear whether the CFTR defect itself initiates inflammation, a widely held point of view is explained by the “Isotonic Low Volume Hypothesis”. It states that the water permeable airway epithelia regulate the volume of the ASL. In the CF airways the abnormal sodium absorption in combination with the failure to secrete chloride leads to an overall loss of water and hence a depletion in the volume of the ASL [22]. The cAMP-dependent Cl^- channel activity of CFTR facilitates the release of ATP, which is involved in the down-regulation of the epithelial sodium channel (ENaC), which accounts for the bulk of salt and water

transport in the airways [23-25]. ENaC is expressed in the airways and the alveolar epithelium and it is the channel responsible for sodium reabsorption, helping maintain a constant depth of the airway surface fluid [26] As the imbalance in sodium is created toward the inside of the epithelial cells, water follows the osmotic gradient depleting the ASL. This leaves a dehydrated low volume ASL that is characterized by thickened mucus and impaired ciliary clearance. It also provides bacteria with tenacious mucus layer to colonize consequently leading to chronic infection[8,27,28] (FIGURE 1). Although there is strong evidence for underhydration of the sol layer of the airway surface liquid, there is not an obvious reason why P. aeruginosa would infect an underhydrated airway surface preferentially. A number of studies have shown qualitative alterations in mucus glycoproteins as well, including changes in sulfation, fucosylation, and sialylation. Some studies have shown an increase in P. aeruginosa binding in CF epithelial cells, while others have shown a decrease in cellular internalization of bacterial pathogens in CF.

However what still remains enigmatic is the observed alterations in innate and adaptive immune responses to certain pathogens. Specifically altered responses to Pseudomonas aeruginosa and Aspergillus fumigatus, with a peculiar increase in neutrophil chemo-attractants in the former case, and a hyper-IgE-like state in the latter are common in CF which predisopes these patients to Allergic broncho-pulmonary aspergillosis (ABPA). This is a clinical syndrome characterized by recurrent wheezing and pulmonary infiltrates, an

excessively high total serum IgE, and high IgE and IgG antibodies directed against Aspergillus fumigatus (Af), which is usually found to be colonizing the airways of these patients. ABPA is very common in CF, affecting approximately 15% of all patients [29,30]. It is occasionally seen in patients with asthma, although some studies have shown that up to 50% of asthma patients with ABPA have at least one mutation in the CFTR gene [31-34]. The immune response in ABPA appears to exemplify the IL-4-driven, Th2-predominant response that is seen in CF patients and in the Cftr mutant mouse expression profiling studies [35-38]. Based on this observation, we have recently described an ABPA-like model in CF mice [39]. In subsequent studies we observed divergent cytokine production in splenocytes from the Cftr mutant mice challenged with Af antigen [40]. This led us to question whether the differences in inflammatory signaling that are apparent in CF mice, are due to the direct or indirect effects of Cftr mutations within non-epithelial cell types, such as lymphocytes.

This question has been raised a number of times in previous work [41,42]. Studies conducted immediately following the discovery of CFTR, indicated that lymphocyte chloride transport was defective in CF and that this could affect function under certain circumstances [43]. A number of other studies have shown that CFTR gene replacement could restore lymphocyte channel activity to normal [44,45]. Finally, the Th2-bias of CF lymphocytes has been confirmed by a number of investigators [36,37]. The unresponsiveness of CF lymphocytes against P. aeruginosa has been known since the late 1970s [46-52], and recent insights are

beginning to shed some light on these observations. Central to the CF T-cell phenotype appears to be a predilection to mount a type 2 helper T-cell (Th2) response [36], which is pro-allergic and appropriate for fighting parasites, but not pathogens such as P. aeruginosa. Indeed, clinical data shows that approximately 10% of CF patients develop Allergic Bronchopulmonary Aspergillosis (ABPA) upon exposure to A. fumigatus [33,53], with increased levels of IL-4, IL-13, and IgE in what appears to be a hyper-inflammatory Th2-dominated immune response [54]. As mentioned above in CF mice, increased levels of IgE are observed compared to controls after exposure to A. fumigatus [39,55], accompanied by a significant shift to a predominantly IL-4 and IL-13 cytokine profile, and a greater sensitivity of CF B-cells to IL-4 stimulation [37].

There is some evidence that T-cell and macrophage unresponsiveness to P. aeruginosa may be the result of Th2 skewing in CF. Moss et al showed that helper T-cells from CF patients produce lower levels of IFN-g, a Th1 cytokine, and higher levels of IL-10, a Th2 cytokine [56]. IL-10 expression in CF has been a subject of debate, but it has been confirmed to be up-regulated by Casaulta et al [57]. This is interesting because the ability of IL-10 to down-regulate IFN-gamma production and decrease co-stimulatory molecules on macrophages can hinder antigen presentation and a proper immune response to P. aeruginosa, A. fumigatus, and other pathogenic species. Further studies are needed to establish if antigen-presentation by macrophages is indeed compromised.

A Th1 immune response may in fact be critical for successfully clearing P. aeruginosa infection. Moser et al showed that when CFTR-/- mice are repeatedly infected with P. aeruginosa, recovery from infection is accompanied by a shift to a Th1 response and increased levels of IL-12, but no change in IgG levels [58]. The surviving mice are resistant to re-infection and have improved mortality. Interestingly, CF mice colonized with P. aeruginosa actually have a higher antibody titer against P. aeruginosa antigens than do colonized wild-type mice, but still develop chronic infection [59]. This suggests that a TH1-type immune response is protective against P. aeruginosa infection independent of antibody production, and compels us to examine the mechanism of a CFTR-mediated defect in T-cells which seems to favor inappropriate Th2 differentiation.

One emerging explanation for the phenomenon of Th2 skewing is the hypothesis that mutant Cftr causes increased Ca2+ flux across the T-cell membrane, thereby perturbing Ca2+ sensitive gene expression pathways. Ca2+ influx is known to be critical for T-cell activation, and is tightly regulated by a number of ion channels, including Cftr [60].

While the downstream effects of Cftr dysfunction are important, it is events at the cell membrane that ultimately drive the Cftr-mediated gene expression aberrations in T-cells and warrant further attention. In 2001, Fanger et al [61] showed that Ca2+ entry in Jurkat T-cells results in activation of KCa channels, creating an efflux of K+ ions which prevents cell membrane depolarization and allows continued Ca2+ entry; these Ca2+ levels are sufficiently high to cause the

signaling necessary for transcriptional activation. If so, then defective Cftr function and subsequent intracellular retention of Cl- ions would be expected to further hyperpolarize the T-cell membrane and augment Ca2+ activated signaling. It is worth noting that the Orai1/Stim1 complex, is also present in the T-cell membrane; studies are needed to determine whether it is similarly affected by mutant Cftr and leading to abnormal gene expression.

Recent insights in T-cell electrophysiology are also giving new perspective to local Cftr functions in the T-cell membrane. According to Cahalan & Chandy [62], some ion channels (Orai1, STIM1, Kv1.3, and KCa3.1) cluster at the antigen presentation site following contact with an antigen-presenting cell (APC). They hypothesize that this clustering could be important for stabilizing the interaction between the T-cell and the APC, and also in generating large extracellular K+ concentrations sufficient to depolarize both the APC and the T-cell. This may be important for efficient antigen presentation, as MHC class II molecule expression on dendritic cells has been shown to double within a minute of K+ induced depolarization [63]. The downstream effects of this may be speculated, yet regardless, these mechanisms may be affected by the lack of functional Cftr at the cell membrane. The work presented in this thesis begins to explore the role of CFTR in T-cell as it relates to the development of allergic responses to *aspergillus fumigatus*, in addition it attempts to provide a possible mechanism for the difference in T-cell responses seen in Cftr deficient lymphocytes.

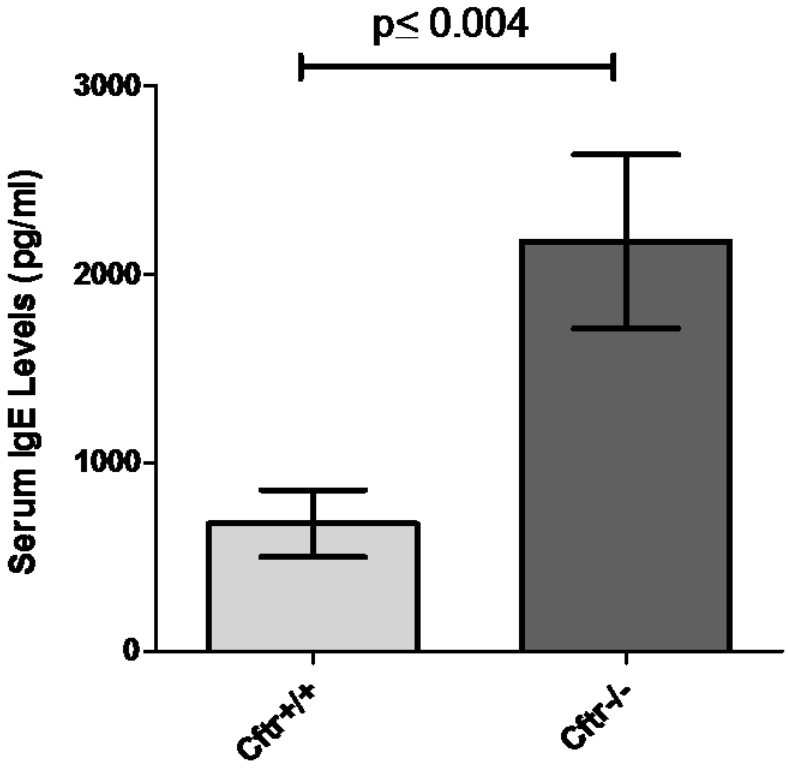
TRANSITION TO RESULTS AND DATA

CHAPTER II: Results

Cftr deficiency and Th2 skewed adaptive immune responses

In previous studies we have shown that Cftr-/- mice on a mixed background had IgE levels that were 2-5 fold higher than their controls when sensitized and airway challenged with Aspergillus fumigatus crude protein extract (Af-cpe)[39]. Furthermore, this phenotype was partially corrected after Cftr gene replacement with recombinant adeno-associated vectors[40]. Here we further establish this phenotype by comparing total serum IgE levels in Cftr-/- mice that are on a congenic C57BL6 background. Cftr-/- and Cftr+/+ littermates were sensitized and challenged with Af-cpe as previously described. Total serum IgE from congenic mice littermates challenged with Af-cpe were on average two-fold higher for Cftr-/- mice (figure 1).

Figure 1. *Total serum IgE levels in congenic C57B6-CFTR-/- mice and their littermates after Af sensitization and challenge*. Mice were sensitized with 200ug of Af crude extract dissolved in 100ul of PBS on day 1 and day 14. Blood samples were collected on day 32; 48hrs after the 3rd aerosol Af challenge. Total Serum IgE in the Af-sensitized mice were measured by ELISA. Data is shown as group averages + S.E.M

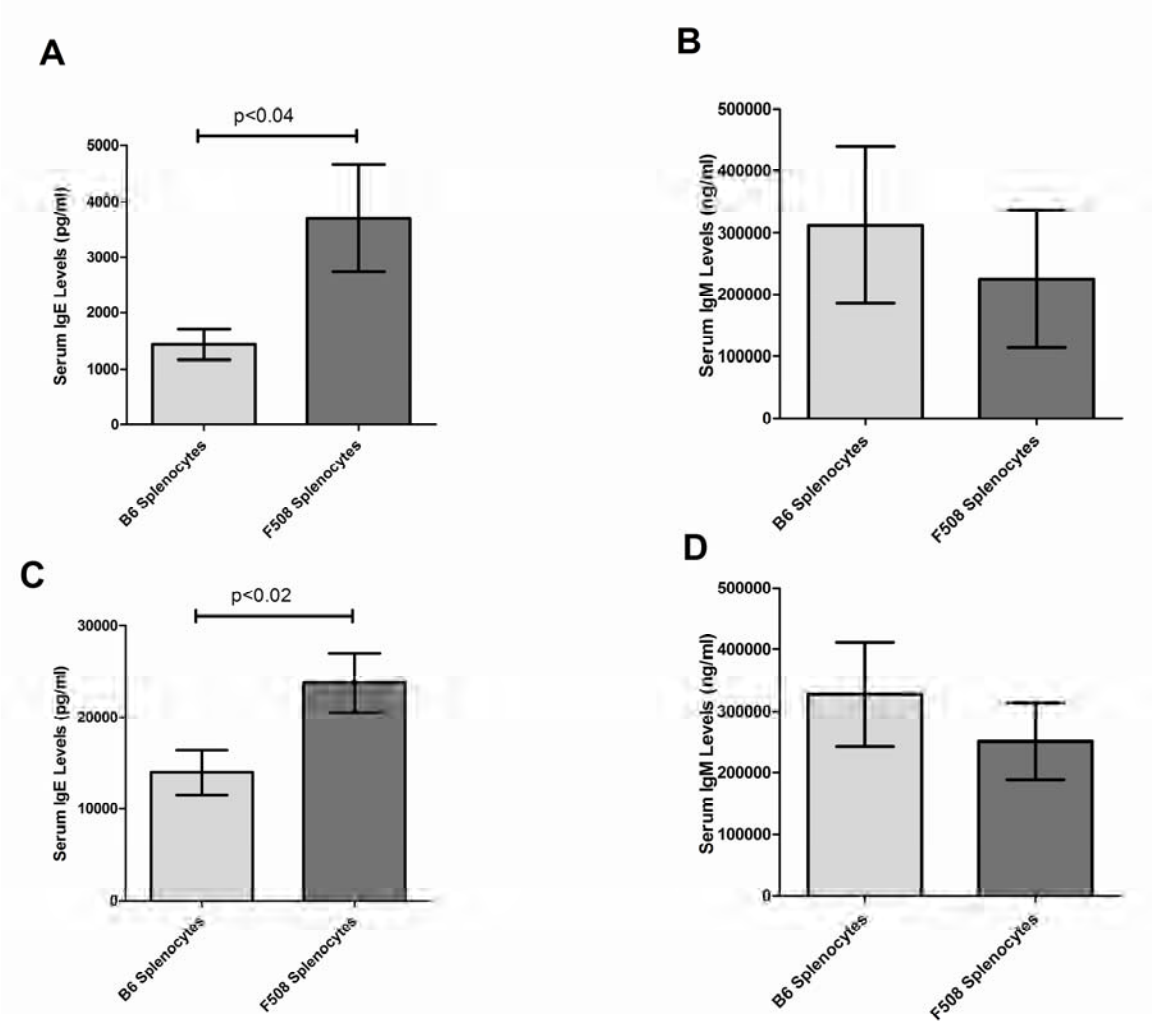

p≤ 0.004
3000
2000
1000
0
Serum IgE Levels (pg/ml)
Cftr+/+
Cftr-/-

Adoptive transfer confers CF-like phenotype

To determine if the altered immune milieu imparted by Cftr-/- lung epithelial cells seen during the aerosol challenge was involved in generating the two-fold higher IgE response towards Af-cpe, we designed adoptive transfer experiments into Rag-/- mice hosts that where otherwise normal for Cftr. In the first set of experiments Cftr-/- mice with a deletion of phenylalanine at amino acid position 508 of the Cftr gene (ΔF508, the most common mutation in the CF population) were sensitized but not airway challenged with Af-cpe. We then harvested splenocytes from these mice and their wildtype littermate controls and adoptively transferred them via an intra-peritoneal injection into Rag-/- mice of the same C57BL6 genetic background. Eight weeks post transfer the Rag-/- mice were airway challenged with aerosolized Af-cpe. Since Rag-/- are deficient in T and B cells and can not produce IgM, total circulating IgM levels were measured on these mice to verify the engraftment of the adoptive transfer (Figure 2b). In order to determine if sensitized splenocytes from CF mice alone were able to recapitulate the high IgE phenotype in the presence of a wildtype (Cftr+/+) airway, sera from the adoptively transferred Rag-/- mice were checked for IgE levels. The results indicate that the two-fold enhanced IgE phenotype is transferred into the host purely by the adoptive transfer of sensitized splenocytes (Figure 2a). To further rule out the possibility of other Cftr-deficient tissues having an effect on the sensitization of the immune cells that were transferred, we repeated these experiments by transferring naïve splenocytes into naive Rag-/-

mice. Eight weeks after the naïve splenocyte transfer, Rag-/- mice were sensitized and airway challenged with Af-cpe. Once again the experiments recapitulated the hyper-IgE phenotype as serum levels of Rag-/- mice receiving CF splenocytes were also two-fold higher than Rag-/- mice receiving wildtype splenocytes (Figure 2c). In contrast, IgM levels in these two groups were not different, confirming that the difference in IgE antibodies levels was not due to differences in B-cell engraftment (Figure 2d).

Figure 2. *Adoptive transfer of CF splenocytes confers elevated IgE phenolype*. CFTR-ΔF508 (CFTR-/-) mice on the B6 background or matched control C57BL/6 mice (CFTR+/+) were used as donors for splenocyte adoptive transfer into B6-Rag-/- mice. Total serum IgE (A, C) and IgM (B, D) were measured after Af challenge. A,B) CFTR-ΔF508 (n=6) and C57BL/6 littermates (n=6) were sensitized with Af-cpe, two weeks after sensitization their splenocytes were transferred into Rag-/- mice where they were allowed to engraft for 8 weeks prior to airway challenging the mice. C, D) Naïve CFTR-ΔF508 (n=10) and naïve C57BL/6 littermates (n=10) were used to harvest naïve splenocytes for transfer into Rag-/- mice. Splenocytes were allowed to engraft for eight weeks and then Rag-/- mice were sensitized and airway challenged with Af-cpe.

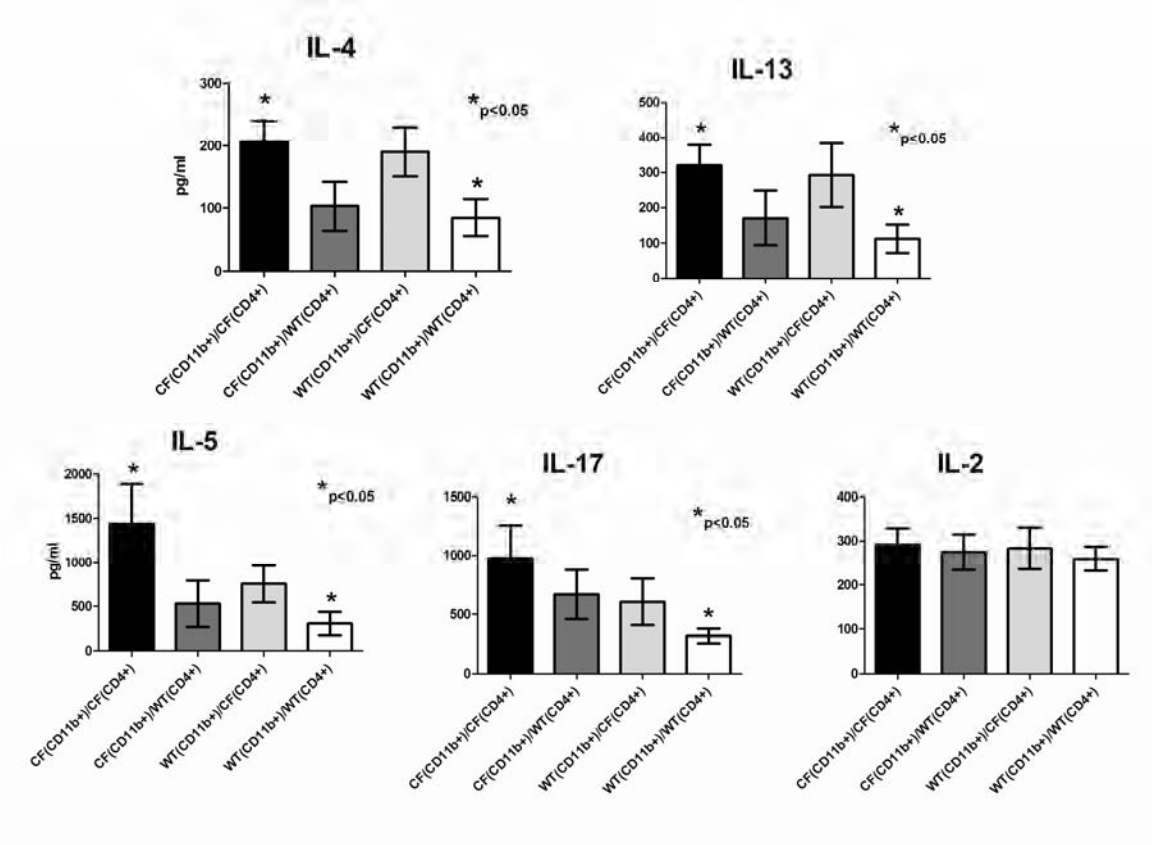

A
p<0.04
Serum IgE Levels (pg/ml)
5000
4000
3000
2000
1000
0
B6 Splenocytes
F508 Splenocytes
B
Serum IgM Levels (ng/ml)
500000
400000
300000
200000
100000
0
B6 Splenocytes
F508 Splenocytes
C
p<0.02
Serum IgE Levels (pg/ml)
30000
20000
10000
0
B6 Splenocytes
F508 Splenocytes
D
Serum IgM Levels (ng/ml)
500000
400000
300000
200000
100000
0
B6 Splenocytes
F508 Splenocytes

Purified CF cell populations demonstrate CF phenotype ex vivo

We then designed a series of antigen recall experiments in order to begin determining what cell population of the splenocytes was responsible for polarizing the adaptive immune responses along aTh2 pathway ultimately leading to the enhanced IgE response seen with the adoptive transfers. In these experiments, splenocytes from mice that had been sensitized to ovalbumin (OVA) were magnetically sorted into either CD4+ lymphocytes or CD11b+ monocytes. The rationale was that upon OVA stimulation in vitro the monocytes would process the antigen and present it to the OVA specific T cells, allowing one to monitor the cytokine profiles secreted in response to a specific antigen. To determine if the Th2 polarization seen with CF splenocytes was due to either antigen presentation or to the antigen-specific response by T-cells the magnetically sorted cell populations were paired in the following configuration; CF monocytes with CF T-cells, CF monocytes with wildtype T-cells, wildtype monocytes with CF T-cells or wildtype monocytes with wildtype T-cells. These experiments uncovered three main cytokine secretion patterns, the first one is evidenced with the Th2 cytokines IL-4 and IL-13, where the elevated secretion seen with CF splenocytes was dependent on whether the stimulated cells had CF CD4+ T cells and was independent of the monocyte source (figure 3a &b). A different cytokine secretion pattern was observed for IL-17 and IL-5; this one was synergistic and dependent on whether both the antigen present cell population (Cd11b+) and the effector cell population (CD4+) were Cftr-/- (figure 3c & d).

Finally IL-2 secretion was similar among all combinations demonstrating that the altered cytokine secretion patterns are not an experimental artifact resulting from the cell mixtures (figure 3e).

Figure 3. *In vitro Antigen Recall with mixed cell populations.* Splenocytes from congenic CFTR-/- or CFTR+/+ mice sensitized to ovalbumin were separated into both CD11b+ and CD4+ cell population with magnetic beads. Cells were mixed and 'crossed' to make four groups of cell preparations; 1) CF CD11b+ with CF CD4+ cells, 2) CF CD11b+ with Wt CD4+ cells, 3) Wt CD11b+ with CF CD4+ cells and 4) Wt CD11b+ with Wt CD4+ cells. Cells were then stimulated with OVA for 5 days. The cell culture supernatants were analyzed for cytokine profiles at day 5. Data is shown as group averages + S.E.M


IL-4
pg/ml
300
200
100
0
*
*p<0.05
*
CF(CD11b+)/CF(CD4+)
CF(CD11b+)/WT(CD4+)
WT(CD11b+)/CF(CD4+)
WT(CD11b+)/WT(CD4+)
IL-13
500
400
300
200
100
0
*
*p<0.05
*
CF(CD11b+)/CF(CD4+)
CF(CD11b+)/WT(CD4+)
WT(CD11b+)/CF(CD4+)
WT(CD11b+)/WT(CD4+)
IL-5
pg/ml
2000
1500
1000
500
0
*
*p<0.05
*
CF(CD11b+)/CF(CD4+)
CF(CD11b+)/WT(CD4+)
WT(CD11b+)/CF(CD4+)
WT(CD11b+)/WT(CD4+)
IL-17
1500
1000
500
0
*
*p<0.05
*
CF(CD11b+)/CF(CD4+)
CF(CD11b+)/WT(CD4+)
WT(CD11b+)/CF(CD4+)
WT(CD11b+)/WT(CD4+)
IL-2
400
300
200
100
0
CF(CD11b+)/CF(CD4+)
CF(CD11b+)/WT(CD4+)
WT(CD11b+)/CF(CD4+)
WT(CD11b+)/WT(CD4+)

Aberrant immune responses result from Cftr-deficient lymphocytes in a conditional knockout model

To confirm the hypothesis that deficiency of a functional CFTR channel in T cells results in Th2 biased adaptive immune response and leads to higher IgE levels, we used conditional Cftr knockout mice. These studies were carried out by crossing the recently described Cftr floxed mice [64] with mice expressing Cre recombinase under the control of the leukocyte-specific protein tyrosine kinase (Lck) promoter, which drives expression of Cre recombinase in CD3+ lymphocytes, resulting in the knockout of the Cftr gene in both CD4+ and CD8+ T-cells.

The floxed Cftr gene was maintained as a homozygous allele and mice were crossed to yield both mice that were Lck-Cre+, and thus Cftr deficient in the T-cell population and mice that were Cre- and thus maintaining the functional floxed Cftr gene in all tissues and cell types. Interestingly, measurement of IgE levels in naïve mice that were Lck-Cftr-/- showed a significant upregulation of serum IgE even at basal levels when compared to their littermate controls (figure 4). This suggests an inherently Th2-biased commitment of Cftr deficient T-cells even in the absence of stimulation. Next we sensitized and airway challenged these mice along with their littermate controls with Af-cpe. The results further confirmed a role for Cftr expression in T cells as evidence by the divergence in serum IgE levels developing at day 21 (1 week after the 2nd i.p injection) and through day 32 (48 hrs after the final aerosol challenge) (figure 5).

Figure 4. *Total Serum IgE Levels in Naïve Conditional CFTR Knockout Mice.* T-cell conditional knockout mice created by crossing the floxed Cftr mouse with mice expressing the Cre recombinase from and LCK promoter where compared to controls that where Cftr floxed but Cre recombiase negative. Basasl serum IgE levels were analyzed by ELISA. Data is shown as group averages + S.E.M

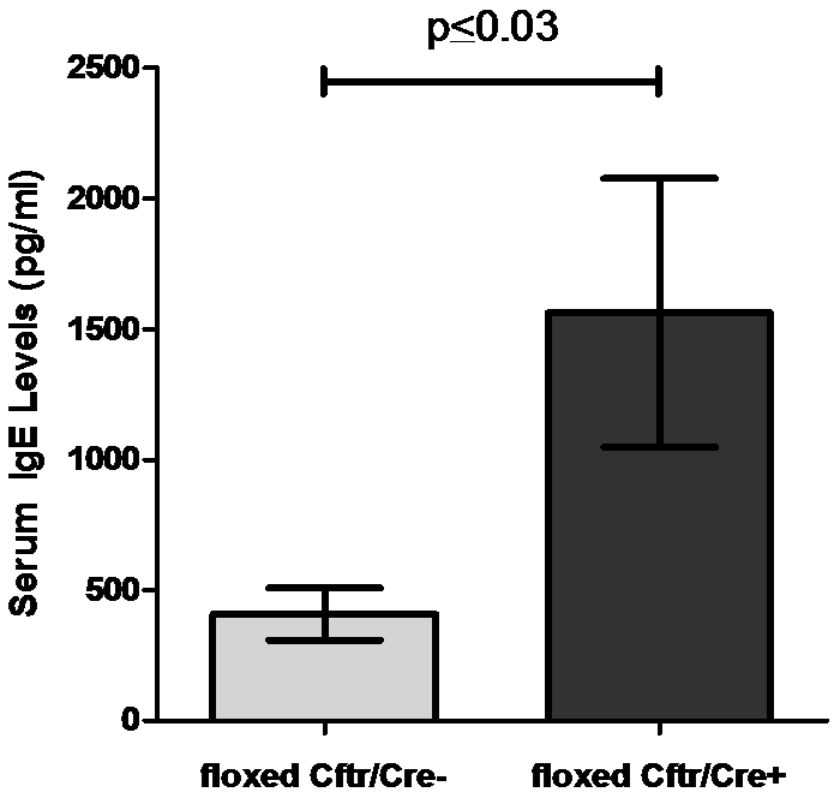
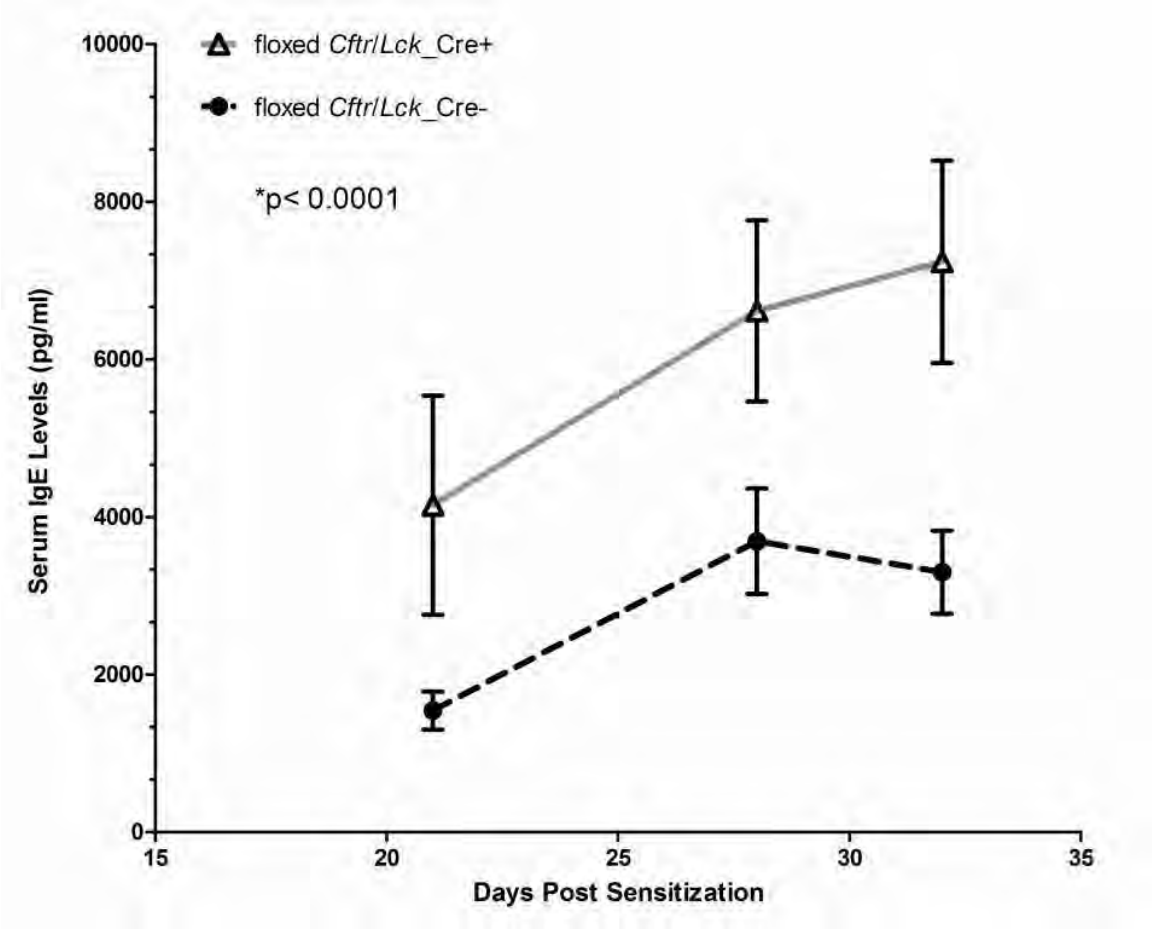

p≤0.03
2500
2000
1500
1000
500
0
Serum IgE Levels (pg/ml)
floxed Cftr/Cre-
floxed Cftr/Cre+

Figure 5. *Total Serum IgE Levels in Af-cpe Sensitized Conditional CFTR Knockout Mice*. T-cell Cftr knockout mice (Cftr floxed and LCK Cre+) along with wildtype controls (Cftr floxed and Cre-) were sensitized with 200ug of Af crude extract dissolved in 100ul of PBS on day 1 and day 14. Blood samples were collected on days 21, 28 and 32. Total Serum IgE in the Af-sensitized mice were measured by ELISA. Data is shown as group averages + S.E.M


floxed Cftr/Lck_Cre+
floxed Cftr/Lck_Cre-
*p< 0.0001
Serum IgE Levels (pg/ml)
10000
8000
6000
4000
2000
0
15
20
25
30
35
Days Post Sensitization

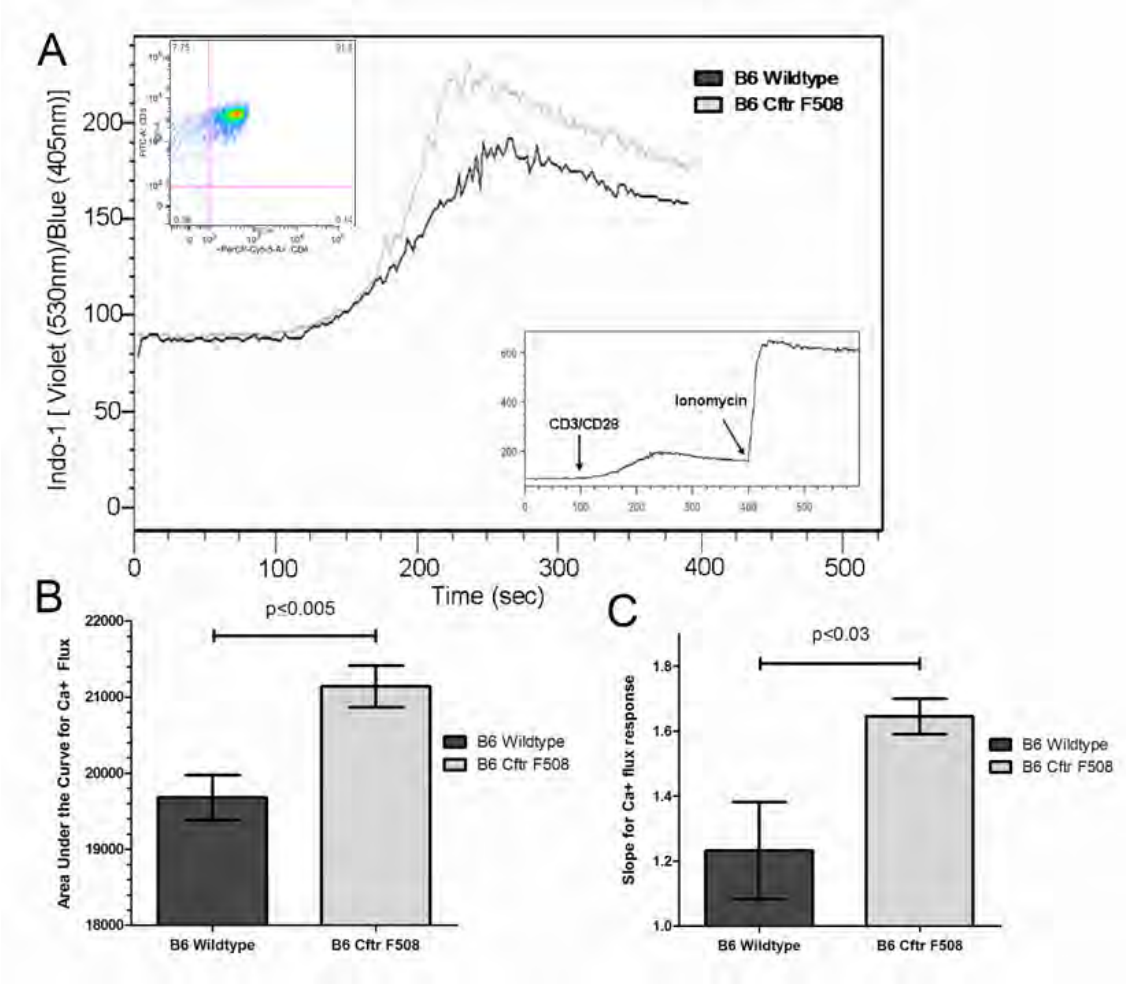
Altered calcium signaling and NFAT activation

To begin to elucidate possible mechanisms for the CFTR channel altering lymphocyte activation, we turned to a recently described model suggesting a link between CFTR and intracellular calcium (iCa2+). While, iCa2+ concentration can be controlled by a myriad of mechanisms that may involve calcium channels, plasma membrane Ca2+ ATPase pumps, and potassium channels among others. The model linking the Cftr mutation to altered iCa2+ and its eventual signaling and inflammation suggests that CFTR through its effect on cell membrane potentials alters the electrical driving force for Ca2+ to enter the cells. In Cftr+/+ T84 intestinal epithelial cells it has been demonstrated that changes in membrane potentials caused expected changes in iCa2+ during agonist activation of calcium entry pathways [65,66]. Thus, with a reduction in Cl- permeability in Cftr-/- cells their membranes can hyperpolarize and it is therefore predicted that Ca2+ entry across the cell membrane would be increased. Alterations in this pathway are important because in lymphocytes iCa2+ initiates a signal transduction pathway through calmodulin and calceneurin eventually leading to the activation of Nuclear factor of activated T-cells (NFAT), which has been shown to enhance gene expression of IL-4, IL-13, IL-5, TNF-alpha cytokines among others [67].

To investigate this hypothesis and whether the absence of the CFTR channel in T cells would have an effect iCa2+ signaling through the T cell receptor (TCR), we measured intracellular calcium fluxes in CD4+ T-cells in

response to CD3/CD28 stimulation of the TCR. Measurements of intracellular calcium in CD4+ T cells using the calcium sensitive Indo-1 dye revealed a significantly greater and enhanced calcium flux response in Cftr deficient T cells (Figure 6).

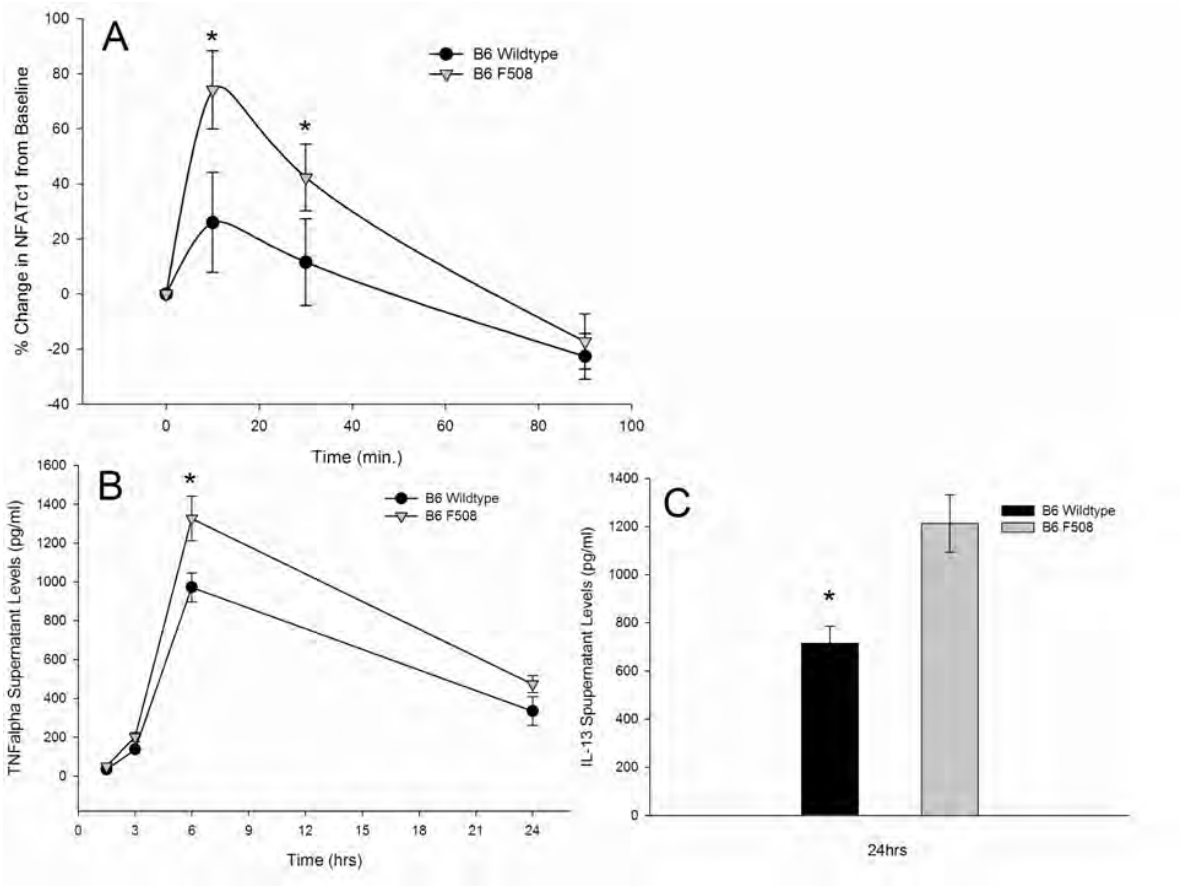
Figure 6. *Intracellular Calcium Flux.* Changes in the concentration of intracellular free Ca2+ ions are measured by monitoring the change in its emission spectrum of Indo-1 dye from blue to violet upon binding to Ca2+. The blue emission is measured through a 530/30 BP filter and the violet through a 405/20 BP and 405 LP filter, thus a shift in the violet/blue ratio over time is a reflection of the increase in intracellular Ca2+ concentration. CD4+ cells were enriched (see inset panel top left) from Cftr-ΔF508 and Cftr+/+ mice and stimulated with anti-CD3/CD28 antibodies followed by 500ng/ml of ionomycin (as a positive control see inset on bottom right). A) Representative intracellular calcium flux for Cftr-ΔF508 and Cftr+/+ CD4+ T cells. B) The area under the curve for the traces from Cftr-ΔF508 (n=6) and Cftr+/+ (n=6) in response to CD3/CD28 Abs. C) The slopes for the traces from Cftr-ΔF508 (n=6) and Cftr+/+ (n=6) in response to CD3/CD28 Abs.


A
Indo-1 [Violet (530nm)/Blue (405nm)]
Time (sec)
B6 Wildtype
B6 Cftr F508
CD3/CD28
Ionomycin
B
Area Under the Curve for Ca+ Flux
p≤0.005
B6 Wildtype
B6 Cftr F508
C
Slope for Ca+ flux response
p<0.03
B6 Wildtype
B6 Cftr F508

To show that the increased intracellular calcium fluxes seen in TCR activation in response to CD3/CD28 results in nuclear accumulation of NFAT, we performed a time course where we stimulated T cells from splenocyte preparations with the same CD3/CD28 antibody cocktail. Nuclear extracts from the stimulated cells were prepared and used to measure NFAT levels. The results confirm that NFAT is translocated to the nucleus in a time sensitive manner after TCR activation by CD3/CD28 and that this nuclear localization is increased in Cftr deficient T cells (figure 7).

To directly show if this nuclear translocation of NFAT would also translate to an upregulation and increased secretion of IL-13 in Cftr-/- T-cells, we measured the cytokine levels in the supernatants of CD3/CD28 stimulated cells. The data showed that the secretion pattern of TNF-alpha, an early activated cytokine known to respond to iCa2+ signaling through the T cell receptor [68] mimicked the pattern seen with the nuclear translocation of NFAT and was secreted at significantly higher levels from Cftr-/- T cells (figure 7b). While IL-13 was below detection in the earlier time points it was found to be expressed at significantly higher levels from Cftr-/- T-cells in supernatants collected 24hrs after stimulation (figure 7c).

Figure 7. *NFATc1 Nuclear translocation and cytokine secretion in Cftr-/- and Cftr+/+ mice after T cell receptor stimulation*. A) Nuclear translocation of NFATc1 was measured using a modified ELISA from nuclear splenocyte extracts after CD3/CD28 stimulation at 10, 30, 90 minutes after stimulation. Parallel plated cells were assessed for cytokine expression after CD3/CD28 stimulation at 1.5, 3, 6 and 24 hours. B) Time course expression for TNF-alpha. C) Expression of IL-13 at 24hrs post stimulation. Data is shown as group averages + S.E.M for a total of N=5.


A
B6 Wildtype
B6 F508
% Change in NFATc1 from Baseline
Time (min.)
B
TNFalpha Supernatant Levels (pg/ml)
Time (hrs)
C
IL-13 Spupernatant Levels (pg/ml)
24hrs

CHAPTER III: Discussion

In the present study we demonstrate for the first time that the absence of CFTR in lymphocytes leads to an inherent divergence in the adaptive immune response in vivo. Specifically, in this case it is characterized by an aberrant Th2-biased immune response to aspergillus fumigatus that is dependent on CFTR function in lymphocytes alone. We demonstrated that sensitization and aerosol challenge of Cftr-/- mice and their wildtype controls leads to an enhanced-IgE response in Cftr-/- mice that is reminiscent of CF related allergic asthmatic condition known as allergic broncho-pulmonary aspergillosis (ABPA). While ABPA remains rare outside of the CF population it is very common among CF patients, affecting approximately 15% of them[29,30]. Interestingly, we demonstrated that the transfer of naive Cftr-deficient splenocytes into congenic Rag-/- mice was enough to confer the high IgE response to the Rag-/- mice. These experiments revealed that a CFTR dependent phenotype can be transferred from CF mice into CFTR sufficient hosts purely through splenocytes.

The expression of CFTR in lymphocytes has been well characterized throughout the years, [42,45,69] however the physiological relevance of CFTR expression in lymphocytes is less clear, with some studies implicating it with volume regulation and cytolysis regulation of CD8+ T-cells[70-73]. Other models suggest that activation of Cl- currents by CFTR in response to nitric oxide via a cyclic GMP-dependent mechanism are defective in T cells from CF patients[74]. Importantly, electrophysiological studies document a functional role for CFTR in lymphocytes

by recording a defect in cAMP-dependent Cl- currents in CF- derived lymphocytes using whole cell patch clamp techniques[42,75]. These studies demonstrate the presence and function of CFTR within lymphocytes and lend some credence to the longstanding yet controversial view that a primary immune abnormality is associated with cystic fibrosis. To date it has been difficult to separate aberrant immune response observed in CF from the disease phenotype imparted by epithelial cell dysfunction. Our adoptive cell transfer experiments indicated that a primary immune abnormality was indeed a possibility. Namely, the transfer of naïve splenocytes was able to recapitulate the 2-fold higher IgE response seen in Cftr-/- mice. We further investigated what specific cell type from the splenocyte pool was responsible for this phenotype with in vitro assays. Since the IgE response is known to be driven by Th2 cytokines and we have previously demonstrated that IL-13 is upregulated in Cftr-/- mice challenged with Af-cpe, we designed a series of experiments to analyze the secretion of Th2 cytokines by activated T cells in response to antigen. According to our data, a marked difference in the secretion of IL-4, IL-13, IL-5 and IL-17 was observed from CD4+ and CD11b+ cells that were Cftr deficient. Interestingly, antigen specific responses characterized by increased secretion of IL-4 and IL-13 were only observed in the presence of Cftr-/- CD4+ T cells, whereas the increased secretion of IL-5 and IL-17 seemed to be dependent on a synergistic interaction between both Cftr-/- Cd11b+ and CD4+ cells. Taken together with the adoptive transfer experiments these data suggested that Cftr deficient T-cells imparted a

Th2-skewed response, characterized by increased secretion of IL-4 and IL-13 ultimately leading to the high IgE response directed against Aspergillus fumigatus crude protein extract. However, based on the secretion of IL-5 and IL-17 in the antigen recall experiments, it is conceivable that skewed responses may be due to the interaction of various Cftr deficient immune cells, such as macrophages, dendritic cells and T-cells.

In order to directly determine whether this phenotype can be attributed to Cftr deficient T-cells we created T-cell specific Cftr knockout mice by using a floxed Cftr mouse expressing Cre recombinase under the control of the LCK promoter. These mice presented with an increase in basal IgE levels in the absence of any exogenous antigenic stimulus. These elevated basal IgE circulating antibody levels are consistent with a previous observation in which we recorded higher IgE levels in Cftr-/- mice, as compared to controls which had been mocked-PBS sensitized and challenged with Af-cpe[39]. Furthermore, these T-cell Cftr conditional knockout mice went on to develop dramatically different IgE responses to Af-cpe as was characteristic of Cftr-/- mice. With these experiments we were able to finally demonstrate without any confounding variables a primary immune abnormality associated with cystic fibrosis in vivo, which, to our knowledge has never been shown before.

A consequence of Cftr deficiency in lymphocytes is the reduction in Cl- permeability which in turn may hyperpolarize their membranes. Its hypothesized that the altered membrane potential could then alter the electrical driving force for

Ca2+ to enter the cells. Here we also show that intracellular calcium fluxes in Cftr-/- CD4+ T cells are increased in response to CD3/CD28 stimulation as determined by the area under the curve and the slopes of the Ca2+ flux response when compared to wildytpe CD4+ T cells (figure 6). The relevance of this altered calcium flux in Cftr-/- T-cells is that it may lead to increased transcription activity of Ca2+ regulated transcription factors. Nuclear factor of activated T-cells (NFAT) activity is modulated by cytoplasmic Ca2+ concentration through various Ca2+ associated signaling pathways. Ultimately, increases in cytoplasmic Ca2+ concentration induce NFAT dephosphorylation and NFAT translocation to the nucleus where it binds to cis regulatory elements of target genes as a monomer[76]. This signaling cascade proceeds through calmodulin and calcineurin, a cytoplasmic serine/threonine phosphotase. Calcineurin upregulates NFAT by dephosphorylating serines in the SP-repeats and in the serine rich N terminus region of NFAT exposing the nuclear localization signal, allowing NFAT to translocate to the nucleus[76]. In T cells, TCR stimulation causes an increase in intracellular Ca2+ concentration depleting Ca2+ sequestered ions in the ER, followed by an influx of extra-cellular calcium ions from Ca2+ release activated Ca2+ channels (CRAC)[76]. While NFAT activation regulates a variety of immune processes, NFAT has been found to regulate a number of other promoters for cytokine genes, including those involved in the regulation of Th2 immune responses as IL-4, IL-13, IL-5 and TNF-alpha[77]. In agreement with the results for the intracellular Ca2+ flux experiments we observed a significantly greater

increase in the nuclear translocation of NFAT after TCR activation with CD3/CD28 in Cftr-/- cells (figure 7). Parallel cell experiments demonstrated that following NFAT nuclear translocation Cftr-/- cells had significantly higher expression of TNF-alpha and the key Th2 effector cytokine IL-13. These data suggests that a possible mechanism responsible for the in vivo immune aberration observed in the conditional Cftr T cell knockout mice may be directly related to the more vigorous TCR mediated calcium flux responses leading to an increase translocation of NFAT and higher induction of IL-13 in Cftr-/- T-cells. Exactly how CFTR dysfunction affects Ca2+ signaling in lymphocytes warrants further investigation and the convergence or overlap of other dysregulated pathways related to Cftr deficiency can not be ruled out. There is some evidence of CFTR dysfunction imparting elevated antibody secretion in B cell hybridomas; while these data do not explicitly assess CFTR function in B cells they do suggest that regardless of aberrant or normal B cell function in CF, the upstream events of T cell activation and helper function alone are enough to impart a polarized antibody response even in the presence of B cell with intact CFTR function.

The main pathological features associated with cystic fibrosis are pancreatic cysts that lead to a reduction in the secretion of digestive enzymes as well as chronic airway infections most notably by pseudomonas. While it has been well established and recognized that impaired CFTR function adversely affects the secretory epithelial, the role of CFTR in non-epithelial cells has received less

attention or has largely eluded investigators. Certainly, if the CFTR alters the function of immune cells it should be expected to result in an aberrant immune response which could further compromise patients. In summary our data identifies that CFTR dysfunction in T cells can in of itself lead to aberrant immune responses. Specifically we show how it skews responses to Aspergillus fumigatus, leading to a higher than normal IgE response. This observation itself is reminiscent ABPA, an otherwise rare but prevalent condition in the CF population. These findings represent a new and important cell population to investigate in order to try to prevent or ameliorate aberrant immune responses in people with cystic fibrosis. Thus, current and future drugs targeting cystic fibrosis should determine if their benefits extend to this cell population, alternatively this also opens a new avenue to test small molecule modulators of immune response as a potential therapy for cystic fibrosis.

CHAPTER IV: Materials and Methods

Mouse strains

The Cftr knock-out strain used for these studies was the CFTR S489X -/- neo insertion in C57BL/6 mice developed initially at the University of North Carolina [78] and then modified with the transgenic over expression of gut-specific expression of human CFTR from the fatty acid binding protein (FABP)- promoter in order to prevent intestinal obstruction and improve viability [79]. The other mouse strain used is Cftr-ΔF508 mouse, both mouse strains have been backcrossed 10 generations onto a C57BL/6 mouse. For experiments on conditional knockout mice the recently developed floxed Cftr mouse [64] was crossed with the C57BL/6 mice expressing CRE recombinase under the control of the leukocyte-specific protein tyrosine kinase (LCK) promoter.

Aspergillus sensitization and challenge

Animals were sensitized to aspergillus fumigatus crude protein extract (Af-cpe) (Greer Laboratories). Briefly, animals were administered with intraperitoneal (i.p.) injections of 200ug of Af-cpe extract dissolved in 100ul of PBS on days 0 and 14. Aerosol challenge was performed with 0.25 % Af-cpe for 20 min in a 30x30x20 cm acrylic chamber using a jet nebulizer Pari model LC-D with an air flow of 6 liters/min on days 28, 29 and 30.

Adoptive Transfers

Adoptive transfer were performed by harvesting either Af-cpe sensitized or naïve splenocytes from Cftr-ΔF508 (Cftr-/-) or wildtype littermate controls. Briefly,

spleens were disaggregated in hanks buffer saline and passed through a 20um mesh. Cells were then resuspended in PBS at a concentration of 4.5x108 cell/ml. Rag-/- mice on a C57BL/6 background were then injected intra-peritonaily with 100ul of the suspension. Eight weeks were allowed for engraftment before either challenging or sensitizing and challenging Rag-/- mice.

Antigen Recall

Spleens were harvested and CD4 T cells and CD11b cells were separated using the AutoMACs pro (Miltenyi Biotec). Cells were counted and plated in 96 well round bottom plates so that there were 1 x 105 CD4 T cells and 1 x 105 CD11b positive cells for a total of 2 x 105 cells per well. Cells were cultured in media that contained 10mg/ml Albumin (Sigma). After 3 days supernatants were removed and frozen for cytokine analysis using Luminex Technology (Bio-Rad, Hercules CA).

Intracellular Calcium Flux

Spleens were harvested and CD4 T cells were separated using AutoMACS pro (Miltenyi Biotec). Intracellular Calcium staining was done as previously described [80].

NFAT Studies

Splenocytes from Cftr-ΔF508 (Cftr-/-) or wildtype littermate controls were plated on paired round bottom 96 well plates with RPMI 1640 10% FBS and 1% Pen/Strep at a concentration of 1x105 cells/well. The cells were then stimulated with CD3/CD28 antibody cocktail and wells from one plate were harvested at (10,

30 and 90 min.). For nuclear protein extraction while the other was used to obtain cell culture supernatants at (1.5, 3, 6 and 24 hrs) for cytokine analysis. Nuclear NFAT translocation was assayed from the nuclear extracts using the modified kit TransAM NFATc1 (Active Motif). Cell culture supernatants were analyzed for cytokine secretion profiles using Luminex Technology (Bio-Rad, Hercules CA).

1. Galant, S.P., Norton, L., Herbst, J. & Wood, C. Impaired beta adrenergic receptor binding and function in cystic fibrosis neutrophils. *J Clin Invest* **68**, 253-258 (1981).

2. Dann, L.G. & Blau, K. Exocrine-gland function and the basic biochemical defect in cystic fibrosis. *Lancet* **2**, 405-407 (1978).

3. Durie, P.R., Kent, G., Phillips, M.J. & Ackerley, C.A. Characteristic multiorgan pathology of cystic fibrosis in a long-living cystic fibrosis transmembrane regulator knockout murine model. *Am J Pathol* **164**, 1481-1493 (2004).

4. Wainwright, B. The molecular pathology of cystic fibrosis. *Curr Biol* **1**, 80-82 (1991).

5. Davidson, D.J., Webb, S., Teague, P., Govan, J.R. & Dorin, J.R. Lung pathology in response to repeated exposure to Staphylococcus aureus in congenic residual function cystic fibrosis mice does not increase in response to decreased CFTR levels or increased bacterial load. *Pathobiology* **71**, 152-158 (2004).

6. Pier, G.B. CFTR mutations and host susceptibility to Pseudomonas aeruginosa lung infection. *Curr Opin Microbiol* **5**, 81-86 (2002).

7. Jiang, C., Finkbeiner, W.E., Widdicombe, J.H. & Miller, S.S. Fluid transport across cultures of human tracheal glands is altered in cystic fibrosis. *J Physiol* **501 (Pt 3)**, 637-647 (1997).

8. Widdicombe, J.H. Regulation of the depth and composition of airway surface liquid. *J Anat* **201**, 313-318 (2002).

9. Li, C. & Naren, A.P. Macromolecular complexes of cystic fibrosis transmembrane conductance regulator and its interacting partners. *Pharmacol Ther* **108**, 208-223 (2005).

10. de Bentzmann, S.*, et al.* Asialo GM1 is a receptor for Pseudomonas aeruginosa adherence to regenerating respiratory epithelial cells. *Infect Immun* **64**, 1582-1588 (1996).

11. Zar, H., Saiman, L., Quittell, L. & Prince, A. Binding of Pseudomonas aeruginosa to respiratory epithelial cells from patients with various mutations in the cystic fibrosis transmembrane regulator. *J Pediatr* **126**, 230-233 (1995).

12. Bastonero, S., Gargouri, M., Ortiou, S., Gueant, J.L. & Merten, M.D. Inhibition by TNF-alpha and IL-4 of cationic lipid mediated gene transfer in cystic fibrosis tracheal gland cells. *J Gene Med* **7**, 1439-1449 (2005).

13. Terheggen-Lagro, S.W., Rijkers, G.T. & van der Ent, C.K. The role of airway epithelium and blood neutrophils in the inflammatory response in cystic fibrosis. *J Cyst Fibros* **4 Suppl 2**, 15-23 (2005).

14. Conese, M., Copreni, E., Di Gioia, S., De Rinaldis, P. & Fumarulo, R. Neutrophil recruitment and airway epithelial cell involvement in chronic cystic fibrosis lung disease. *J Cyst Fibros* **2**, 129-135 (2003).

15. Sagel, S.D. & Accurso, F.J. Monitoring inflammation in CF. Cytokines. *Clin Rev Allergy Immunol* **23**, 41-57 (2002).

16. Venkatakrishnan, A.*, et al.* Exaggerated activation of nuclear factor-kappaB and altered IkappaB-beta processing in cystic fibrosis bronchial epithelial cells. *Am J Respir Cell Mol Biol* **23**, 396-403 (2000).

17. Rottner, M., Kunzelmann, C., Mergey, M., Freyssinet, J.M. & Martinez, M.C. Exaggerated apoptosis and NF-kappaB activation in pancreatic and tracheal cystic fibrosis cells. *Faseb J* **21**, 2939-2948 (2007).

18. van Heeckeren, A., Ferkol, T. & Tosi, M. Effects of bronchopulmonary inflammation induced by pseudomonas aeruginosa on adenovirus-mediated gene transfer to airway epithelial cells in mice. *Gene Ther* **5**, 345-351 (1998).

19. van Heeckeren, A.M., Schluchter, M.D., Xue, W. & Davis, P.B. Response to acute lung infection with mucoid Pseudomonas aeruginosa in cystic fibrosis mice. *Am J Respir Crit Care Med* **173**, 288-296 (2006).

20. van Heeckeren, A.M., Schluchter, M.D., Drumm, M.L. & Davis, P.B. Role of Cftr genotype in the response to chronic Pseudomonas aeruginosa lung infection in mice. *Am J Physiol Lung Cell Mol Physiol* **287**, L944-952 (2004).

21. van Heeckeren, A.M.*, et al.* Effect of Pseudomonas infection on weight loss, lung mechanics, and cytokines in mice. *Am J Respir Crit Care Med* **161**, 271-279 (2000).

22. Matsui, H.*, et al.* Evidence for periciliary liquid layer depletion, not abnormal ion composition, in the pathogenesis of cystic fibrosis airways disease [In Process Citation]. *Cell* **95**, 1005-1015 (1998).

23. Jarisch, A., Giunta, C., Zielen, S., Konig, R. & Steinmann, B. Sibs affected with both Ehlers-Danlos syndrome type IV and cystic fibrosis. *Am J Med Genet* **78**, 455-460 (1998).

24. Wagner, C.A.*, et al.* Effects of the serine/threonine kinase SGK1 on the epithelial Na(+) channel (ENaC) and CFTR: implications for cystic fibrosis. *Cell Physiol Biochem* **11**, 209-218 (2001).

25. Kunzelmann, K.*, et al.* No evidence for direct activation of the cystic fibrosis transmembrane conductance regulator by 8-cyclopentyl-1,3-dipropylxanthine. *Cell Physiol Biochem* **8**, 185-193 (1998).

26. Olivier, R., Scherrer, U., Horisberger, J.D., Rossier, B.C. & Hummler, E. Selected contribution: limiting Na(+) transport rate in airway epithelia from alpha-ENaC transgenic mice: a model for pulmonary edema. *J Appl Physiol* **93**, 1881-1887 (2002).

27. Davies, J.C. Pseudomonas aeruginosa in cystic fibrosis: pathogenesis and persistence. *Paediatr Respir Rev* **3**, 128-134 (2002).

28. Middleton, P.G., *et al.* Airway surface liquid calcium modulates chloride permeability in the cystic fibrosis airway. *Am J Respir Crit Care Med* **168**, 1223-1226 (2003).

29. Becker, J.W.*, et al.* Prevalence of allergic bronchopulmonary aspergillosis and atopy in adult patients with cystic fibrosis. *Chest* **109**, 1536-1540 (1996).

30. Skov, M., McKay, K., Koch, C. & Cooper, P.J. Prevalence of allergic bronchopulmonary aspergillosis in cystic fibrosis in an area with a high frequency of atopy. *Respir Med* **99**, 887-893 (2005).

31. Eaton, T.E., Weiner Miller, P., Garrett, J.E. & Cutting, G.R. Cystic fibrosis transmembrane conductance regulator gene mutations: do they play a role in the aetiology of allergic bronchopulmonary aspergillosis? *Clin Exp Allergy* **32**, 756-761 (2002).

32. Marchand, E.*, et al.* Frequency of cystic fibrosis transmembrane conductance regulator gene mutations and 5T allele in patients with allergic bronchopulmonary aspergillosis. *Chest* **119**, 762-767 (2001).

33. Laufer, P.*, et al.* Allergic bronchopulmonary aspergillosis in cystic fibrosis. *J Allergy Clin Immunol* **73**, 44-48 (1984).

34. Miller, P.W.*, et al.* Cystic fibrosis transmembrane conductance regulator (CFTR) gene mutations in allergic bronchopulmonary aspergillosis. *Am J Hum Genet* **59**, 45-51 (1996).

35. Skov, M., Poulsen, L.K. & Koch, C. Increased antigen-specific Th-2 response in allergic bronchopulmonary aspergillosis (ABPA) in patients with cystic fibrosis. *Pediatr Pulmonol* **27**, 74-79 (1999).

36. Hartl, D.*, et al.* Pulmonary T(H)2 response in Pseudomonas aeruginosa-infected patients with cystic fibrosis. *J Allergy Clin Immunol* **117**, 204-211 (2006).

37. Knutsen, A.P.*, et al.* Increased sensitivity to IL-4 in cystic fibrosis patients with allergic bronchopulmonary aspergillosis. *Allergy* **59**, 81-87 (2004).

38. Xu, Y.*, et al.* Transcriptional adaptation to cystic fibrosis transmembrane conductance regulator deficiency. *J Biol Chem* **278**, 7674-7682 (2003).

39. Muller, C.*, et al.* Enhanced IgE allergic response to Aspergillus fumigatus in CFTR-/- mice. *Lab Invest* **86**, 130-140 (2006).

40. Mueller, C.*, et al.* Partial correction of the CFTR-dependent ABPA mouse model with recombinant adeno-associated virus gene transfer of truncated CFTR gene. *J Gene Med* **10**, 51-60 (2008).

41. Bubien, J.K. CFTR may play a role in regulated secretion by lymphocytes: a new hypothesis for the pathophysiology of cystic fibrosis. *Pflugers Arch* **443 Suppl 1**, S36-39 (2001).

42. McDonald, T.V., Nghiem, P.T., Gardner, P. & Martens, C.L. Human lymphocytes transcribe the cystic fibrosis transmembrane conductance regulator gene and exhibit CF-defective cAMP-regulated chloride current. *J Biol Chem* **267**, 3242-3248 (1992).

43. Chen, J.H., Schulman, H. & Gardner, P. A cAMP-regulated chloride channel in lymphocytes that is affected in cystic fibrosis. *Science* **243**, 657-660 (1989).

44. Krauss, R.D., Berta, G., Rado, T.A. & Bubien, J.K. Antisense oligonucleotides to CFTR confer a cystic fibrosis phenotype on B lymphocytes. *Am J Physiol* **263**, C1147-1151 (1992).

45. Krauss, R.D.*, et al.* Transfection of wild-type CFTR into cystic fibrosis lymphocytes restores chloride conductance at G1 of the cell cycle. *Embo J* **11**, 875-883 (1992).

46. Sorensen, R.U., Chase, P.A., Stern, R.C. & Polmar, S.H. Influence of cystic fibrosis plasma on lymphocyte responses to Pseudomonas aeruginosa in vitro. *Pediatr Res* **15**, 14-18 (1981).

47. Sorensen, R.U., Ruuskanen, O., Miller, K. & Stern, R.C. B-lymphocyte function in cystic fibrosis. *Eur J Respir Dis* **64**, 524-533 (1983).

48. Sorensen, R.U., Stern, R.C., Chase, P. & Polmar, S.H. Defective cellular immunity to gram-negative bacteria in cystic fibrosis patients. *Infect Immun* **23**, 398-402 (1979).

49. Sorensen, R.U., Stern, R.C., Chase, P.A. & Polmar, S.H. Changes in lymphocyte reactivity to Pseudomonas aeruginosa in hospitalized patients with cystic fibrosis. *Am Rev Respir Dis* **123**, 37-41 (1981).

50. Sorensen, R.U., Stern, R.C. & Polmar, S.H. Lymphocyte responsiveness to Pseudomonas aeruginosa in cystic fibrosis: Relationship to status of pulmonary disease in sibling pairs. *J Pediatr* **93**, 201-205 (1978).

51. Sorensen, R.U., Stern, R.C. & Polmar, S.H. Cellular immunity to bacteria: impairment of in vitro lymphocyte responses to Pseudomonas aeruginosa in cystic fibrosis patients. *Infect Immun* **18**, 735-740 (1977).

52. Van Geffel, R., Hubert, E. & Josse, M. Study of the relation between the clinical pulmonary condition of children with cystic fibrosis and the lymphoblastic response to the antigen Pseudomonas aeruginosa. *Ann Immunol (Paris)* **133D**, 293-303 (1982).

53. Agarwal, R., Khan, A., Aggarwal, A.N. & Gupta, D. Link between CFTR mutations and ABPA: a systematic review and meta-analysis. *Mycoses* (2011).

54. Knutsen, A.P.*, et al.* Asp f I CD4+ TH2-like T-cell lines in allergic bronchopulmonary aspergillosis. *J Allergy Clin Immunol* **94**, 215-221 (1994).

55. Knutsen, A.P., Hutcheson, P.S., Slavin, R.G. & Kurup, V.P. IgE antibody to Aspergillus fumigatus recombinant allergens in cystic fibrosis patients with allergic bronchopulmonary aspergillosis. *Allergy* **59**, 198-203 (2004).

56. Moss, R.B., Hsu, Y.P. & Olds, L. Cytokine dysregulation in activated cystic fibrosis (CF) peripheral lymphocytes. *Clin Exp Immunol* **120**, 518-525 (2000).

57. Casaulta, C.*, et al.* IL-10 controls Aspergillus fumigatus- and Pseudomonas aeruginosa-specific T-cell response in cystic fibrosis. *Pediatr Res* **53**, 313-319 (2003).

58. Moser, C.*, et al.* Improved outcome of chronic Pseudomonas aeruginosa lung infection is associated with induction of a Th1-dominated cytokine response. *Clin Exp Immunol* **127**, 206-213 (2002).

59. Coleman, F.T.*, et al.* Hypersusceptibility of cystic fibrosis mice to chronic Pseudomonas aeruginosa oropharyngeal colonization and lung infection. *Proc Natl Acad Sci U S A* **100**, 1949-1954 (2003).

60. Balghi, H.*, et al.* Enhanced Ca2+ entry due to Orai1 plasma membrane insertion increases IL-8 secretion by cystic fibrosis airways. *FASEB J* (2011).

61. Fanger, C.M.*, et al.* Calcium-activated potassium channels sustain calcium signaling in T lymphocytes. Selective blockers and manipulated channel expression levels. *J Biol Chem* **276**, 12249-12256 (2001).

62. Cahalan, M.D. & Chandy, K.G. The functional network of ion channels in T lymphocytes. *Immunol Rev* **231**, 59-87 (2009).

63. Vukcevic, M., Spagnoli, G.C., Iezzi, G., Zorzato, F. & Treves, S. Ryanodine receptor activation by Ca v 1.2 is involved in dendritic cell major histocompatibility complex class II surface expression. *J Biol Chem* **283**, 34913-34922 (2008).

64. Hodges, C.A., Cotton, C.U., Palmert, M.R. & Drumm, M.L. Generation of a conditional null allele for Cftr in mice. *Genesis* **46**, 546-552 (2008).

65. Machen, T.E. Innate immune response in CF airway epithelia: hyperinflammatory? *Am J Physiol Cell Physiol* **291**, C218-230 (2006).

66. Fischer, H., Illek, B., Negulescu, P.A., Clauss, W. & Machen, T.E. Carbachol-activated calcium entry into HT-29 cells is regulated by both membrane potential and cell volume. *Proc Natl Acad Sci U S A* **89**, 1438-1442 (1992).

67. Peng, S.L., Gerth, A.J., Ranger, A.M. & Glimcher, L.H. NFATc1 and NFATc2 together control both T and B cell activation and differentiation. *Immunity* **14**, 13-20 (2001).

68. Kaminuma, O.*, et al.* Differential contribution of NFATc2 and NFATc1 to TNF-alpha gene expression in T cells. *J Immunol* **180**, 319-326 (2008).

69. Yoshimura, K.*, et al.* Expression of the cystic fibrosis transmembrane conductance regulator gene in cells of non-epithelial origin. *Nucleic Acids Res* **19**, 5417-5423 (1991).

70. Grinstein, S., Rothstein, A., Sarkadi, B. & Gelfand, E.W. Responses of lymphocytes to anisotonic media: volume-regulating behavior. *Am J Physiol* **246**, C204-215 (1984).

71. Lee, S.C., Price, M., Prystowsky, M.B. & Deutsch, C. Volume response of quiescent and interleukin 2-stimulated T-lymphocytes to hypotonicity. *Am J Physiol* **254**, C286-296 (1988).

72. Prochazka, G., Landon, C. & Dennert, G. Transmembrane chloride flux is required for target cell lysis but not for Golgi reorientation in cloned cytolytic effector cells. Golgi reorientation, N alpha-benzyloxycarbonyl-L-lysine thiobenzyl ester serine esterase release, and delivery of the lethal

hit are separable events in target cell lysis. *J Immunol* **141**, 1288-1294 (1988).

73. Gray, L.S. & Russell, J.H. Cytolytic T lymphocyte effector function requires plasma membrane chloride flux. *J Immunol* **136**, 3032-3037 (1986).

74. Dong, Y.J.*, et al.* Activation of CFTR chloride current by nitric oxide in human T lymphocytes. *Embo J* **14**, 2700-2707 (1995).

75. Bubien, J.K., Kirk, K.L., Rado, T.A. & Frizzell, R.A. Cell cycle dependence of chloride permeability in normal and cystic fibrosis lymphocytes. *Science* **248**, 1416-1419 (1990).

76. Crabtree, G.R. & Olson, E.N. NFAT signaling: choreographing the social lives of cells. *Cell* **109 Suppl**, S67-79 (2002).

77. Rao, A., Luo, C. & Hogan, P.G. Transcription factors of the NFAT family: regulation and function. *Annu Rev Immunol* **15**, 707-747 (1997).

78. Grubb, B.R.*, et al.* Inefficient gene transfer by adenovirus vector to cystic fibrosis airway epithelia of mice and humans. *Nature* **371**, 802-806 (1994).

79. Zhou, L.*, et al.* Correction of lethal intestinal defect in a mouse model of cystic fibrosis by human CFTR. *Science* **266**, 1705-1708 (1994).

80. June, C.H., Abe, R. & Rabinovitch, P.S. Measurement of intracellular calcium ions by flow cytometry. *Curr Protoc Cytom* **Chapter 9**, Unit 9 8 (2001).