Hnf4α is a key gene that can generate columnar metaplasia in oesophageal epithelium


ABSTRACT

Barrett’s metaplasia is the only known morphological precursor to oesophageal adenocarcinoma and is characterized by replacement of stratified squamous epithelium by columnar epithelium. The cell of origin is uncertain and the molecular mechanisms responsible for the change in cellular phenotype are poorly understood. We therefore explored the role of two transcription factors, Cdx2 and HNF4α, in the conversion using primary organ cultures. Biopsy samples from cases of human Barrett’s metaplasia were analysed for the presence of CDX2 and HNF4α. A new organ culture system for adult murine oesophagus is described. Using this, Cdx2 and HNF4α were ectopically expressed by adenoviral infection. The phenotype following infection was determined by a combination of PCR, immunohistochemical and morphological analyses. We demonstrate the expression of Cdx2 and HNF4α in human biopsy samples. Our oesophageal organ culture system expressed markers characteristic of the normal SSQE: p63, K14, K4 and loricrin. Ectopic expression of HNF4α, but not of Cdx2 induced expression of Tgf3, villin, K8 and E-cadherin. HNF4α is sufficient to induce a columnar-like phenotype in adult mouse oesophageal epithelium and is present in the human condition. These data suggest that induction of HNF4α is a key early step in the formation of Barrett’s metaplasia and are consistent with an origin of Barrett’s metaplasia from the oesophageal epithelium.

1. Introduction

Barrett’s metaplasia (BM) is a pathological condition characterized by replacement of stratified squamous epithelium (SSQE) of the distal oesophagus by columnar epithelium (Fitzgerald, 2006; Spechler and Goyal, 1996). BM is found in the context of gastro-oesophageal reflux disease (GORD) and arises as a consequence of the damage provoked by acid and bile (Vaezi and Richter, 1996; Falk, 2002). The condition is characterized by replacement of stratified squamous epithelium by columnar epithelium (Fitzgerald, 2006; Souza et al., 2008; Spechler et al., 2010; Chen et al., 2011; Quinlan et al., 2007). Plausible candidates for the cell of origin, are the oesophageal epithelium itself, the oesophageal glands, or multipotent cells residing near the oesophageal-gastric junction (Coad et al., 2005; Leedham et al., 2008; Barbera and Fitzgerald, 2010; Wang et al., 2011; Nicholson et al., 2012; Streppel et al., 2014; Clemons et al., 2014).

Several lines of evidence suggest that the caudal related homeobox genes (CDX) 1 and 2 are involved in the initiation of BM (Souza et al., 2008). CDX1 and CDX2 are important transcription factors in the regional patterning of the caudal gut during embryonic development, and in the differentiation of the intestinal epithelium (Gao et al., 2009;...
The expression pattern of both genes is restricted to the endodermal epithelium that is destined to become the small and large intestine (Silberg et al., 2000). Ectopic expression of Cdx2 in the stomach of transgenic mice can cause the formation of heterotopic intestinal epithelium (Mutoh et al., 2004; Silberg et al., 2002). Conversely, selective deletion of gut endodermal Cdx2 during development results in the expression of squamous differentiation markers in the intestine (Gao et al., 2009). Mice heterozygous for a null allele of Cdx2 develop patches of SSQE reminiscent of oesophageal epithelium within the colon and small intestine (Chawengsaksophak et al., 1997). Cdx1 and 2 also control the rostral-caudal pattern of tissue types and body parts: for example, loss of Cdx2 function results in an anterior homeotic shift in vertebrae (Van Den Akker et al., 2002) and intestine (Gao et al., 2009; Chawengsaksophak et al., 1997).

Both CDX1 and CDX2 are aberrantly expressed in BM and in adjacent squamous epithelium (Eda et al., 2003; Silberg et al., 1997). Since the oesophagus is exposed to acid and bile during GORD, this suggests a potential mechanism of action for the initiation of BM (Marchetti et al., 2003; Kazumori et al., 2006). Exposure to acid and bile has been shown to induce expression of Cdx1 and Cdx2 in oesophageal cells in rats (Kazumori et al., 2006). Given the potential role of CDX2 in the development of BM, we wished to determine whether ectopic Cdx2 expression was able to induce a columnar-like phenotype in murine oesophageal cultures.

We were also interested to know whether other transcription factors might be involved in the conversion of SSQE to columnar epithelium.
Hepatocyte nuclear factor 4α (HNF4α), a nuclear receptor type transcription factor, may also be considered as a candidate for the initiation of BM. During early development of the gut, Hnf4α is expressed in the intestine as well as the stomach, kidney, liver and pancreas (Zhong et al., 1993; Taraviras et al., 1994). Importantly, HNF4α is not expressed in normal human oesophagus, but is expressed in BM (Piessen et al., 2007; Green et al., 2014; Wang et al., 2009). Normal epithelial differentiation of the colon and maturation of goblet cells is dependent upon the presence of Hnf4α (Garrison et al., 2006). Therefore, we wanted to know whether ectopic expression of Cdx2 and/or Hnf4α might incite Barrett’s-like changes in squamous cells.

To address the potential role of CDX2 and HNF4α in BM we developed a long-term adult mouse oesophageal explant model. Long-term culture of oesophageal epithelium has proven difficult. Broadly there are two sources of cells available to study BM: immortalized cell lines such as Het-1A, or ex vivo primary cell culture involving either mechanical tissue mincing or enzymatic digestion of oesophageal tissue. Cells or explants have been cultured on a variety of substrates, matrices and scaffolding, including organotypic models with multi-layered squamous cells (Green et al., 2010). While each of these models has advantages and disadvantages, for our purposes we ideally needed the following features: first, the full repertoire of squamous cells expressing basal cell markers (cytokeratin 14 (K14) and p63), differentiating markers (K4 and involucrin) and a terminally differentiated cell marker (lrorcin); second a feeder-free model to simplify characterisation and experimental interpretation; and third cell viability for at least two weeks to allow for gene insertion. None of the existing models satisfied all these criteria. We developed and characterized our oesophageal model, transduced oesophageal explants with adenoviral vectors expressing Cdx2 or HNF4α and analysed the phenotype of the cells.

Our study directly investigated the ability of Cdx2 and HNF4α overexpression to induce an intestinal columnar phenotype in a model of adult oesophageal epithelium. Contrary to previous expectations, but consistent with some other recent studies (Kong et al., 2011, 2009), introduction of Cdx2 did not provoke a columnar phenotype with expression of intestinal genes. However, we found that HNF4α did so. Since we also confirm that HNF4α is expressed in BM, we consider that its ectopic activation is likely to be a key early step in the formation of BM. The fact that the changes are provoked in cultures of normal oesophageal epithelium are consistent with the possibility that BM does arise from the oesophageal epithelium, although cannot exclude the other possibilities.

2. Result

2.1. Expression of Cdx2 and HNF4α along the normal GI tract and in Barrett’s metaplasia

Previous studies have described the expression of CDX2 in Barrett’s epithelium but the involvement of HNF4α is less well documented. Here we demonstrate using immunohistochemical analysis of normal human oesophagus and Barrett’s epithelium that HNF4α protein is indeed present in BM in an identical pattern to that of CDX2 (Fig. 1). HNF4α background staining was not eliminated from the slide sections of oesophagus, but contrast is demonstrated at the gastro-oesophageal section.

2.2. Oesophageal explants are viable in vitro for up to 3 months

We have developed a new culture system for adult mouse oesophagus, to complement the system previously developed for embryonic oesophagus. (Yu et al., 2005). Adult mouse oesophageal explants attached to plastic substratum within 48 h of plating in 82% of cases (41/50). In 95% (39/41) of explants that attached, cells migrated out from the explants within a week (Fig. 2). Two distinct cell morphologies were found around each explant: mesenchymal and epithelial. A central area surrounding the original explant exhibited overlapping cells, comprising a multilayered structure. The size of the outgrowth increased daily for 2–3 weeks before reaching equilibrium and remained viable for up to three months (Fig. 2A; Supplementary Fig 1).

2.3. Characterisation of oesophageal explant cultures

To assess the adult oesophageal explant culture as an in vitro model of squamous oesophagus, cellular phenotypes were characterized by immunofluorescence detection using proteins typically found in the native oesophageal structure. The outgrowth of tissue surrounding the oesophageal explant contained mesenchymal cells expressing smooth muscle actin (SMA, Fig. 2Bi, iii and vii) and E-cadherin-positive epithelial cells (Fig. 2Bi). The majority of outgrowths (36/39; > 90%) contained both epithelial and mesenchymal cell types. A minority of explants contained only SMA-positive cells, but no outgrowth consisted purely of epithelium, suggesting that mesenchymal cells are required for the maintenance of the epithelial cells.

Three different markers of squamous differentiation were examined within the explant cultures: K14 (basal)-, K4 (suprabasal)- and loricrin (the major component of the cornified cell envelope)- expressing cells were all present in the cultures (Fig. 2Bi, iv-xii). K4-positive cells were found above the K14 layer (Fig. 2Bvi and vii). The transcription factor p63, required for the induction and maintenance of the oesophageal SSQE (Daniely et al., 2004), was expressed in two distinct patterns (Fig. 2Bx-xii). The first type of p63-positive cell was found within or immediately adjacent to the explant and lacked K14 expression (Fig. 2Bx and Fig. 3Ciii). The second was in cells co-expressing p63 with K14 and were more commonly located in the area surrounding the explant (Fig. 2Bxi and Fig. 3Ciii). The epithelium surrounding these cells was positive for K14 but negative for p63 (Fig. 3Ciii). The K14/p63 co-expressing cells were covered by a layer of K14-positive cells (Fig. 2Bxii).

2.4. Role of calcium in oesophageal differentiation

Calcium is an essential determinant of epidermal keratinocyte proliferation and differentiation (Hennings and Holbrook, 1983; Hennings et al., 1980). We wished to determine whether SSQE behaves in a similar fashion to skin in its response to calcium. To address this we cultured oesophageal explants in either BME or MDCB 153 medium which contain 1.8 mM (normal) and 0.03 mM (low) calcium respectively (Fig. 3). Explants cultured in normal calcium had a different morphology to those cultured in low calcium (Fig. 3A). Oesophageal cells cultured for seven days in low calcium grew as monolayers, failed to form cell-cell contacts, and did not stratify, as judged by the absence of K4 (Fig. 3Bi). These conditions facilitated quantification of staining and greatly improved viral infection efficiency (see below) In contrast, cells cultured in BME showed robust staining for K4 (Fig. 3Biii vii vs Bi). To test the response to calcium, we cultured oesophageal explants for 5 days in 0.03 mM calcium followed by 3 days at a final concentration of 1 mM calcium (Fig. 3Biv). In low calcium conditions cells did not express K4 (Fig. 3Bii) but after short term exposure to higher concentrations of calcium, K4 became expressed in approximately 25% of the cells (Fig. 3Biv). Expression of p63 was maintained in most (99%) of the cells cultured in low calcium and was co-expressed exclusively with K14. This contrasts with oesophageal explants cultured in normal calcium, where cells expressing K14 alone can be found (Fig. 3C compare ii and iv).

2.5. Cdx2 represses p63 expression but does not induce intestinal genes

We examined the efficacy of the Ad-CMV-Cdx2-eGFP virus in adult oesophageal explants, cultured in low (MDCB 153) and normal (BME)
calcium concentrations, to induce intestinal gene expression (Fig. 4). Explants were grown for 7 days, incubated with medium containing virus for 12 h, and the expression of intestinal markers was assessed by immunofluorescence and RT-PCR after 3 further days of culture. The presence of Cdx2 protein within the nuclei of K14-positive epithelial cells was determined by GFP expression (Fig. 4A and B) and Cdx2 mRNA was detected by RT-PCR (Fig. 4C and D). In cells cultured in normal calcium, incubation with Ad-CMV-Cdx2-eGFP resulted in robust expression of Cdx2 within the majority of epithelial cells (Fig. 4A) with a transfection efficiency of 73%. In low calcium cultures, we initially used the same titre of virus as for the BME cultures but as this resulted in significant cell death the titre was reduced 100-fold to 5×10^5 IU per explant to maintain viability and produce a similar percentage of GFP-positive cells (> 50%) (Fig. 4B) as for the BME cultures. Three days following Cdx2 infection, p63 was lost from some of the cells expressing Cdx2 but not from cells infected with control adenovirus (4.33+/−1.53 cells per high power field lost p63 expression compared with 0.33+/−0.58; p=0.046 Mann-Whitney test) (Supplementary Fig 2). It was only possible to determine the p63 loss because of the monolayer morphology and the fact that the vast majority of cells within the low calcium culture were p63-positive.

Despite the high level of expression of Cdx2 in the low calcium medium, the levels of induction of Mucin2 and Villin RNA were only just detectable (Fig. 4C – 35 cycles of PCR) and were not visible at the protein level. Ectopic expression of Cdx2 did not induce detectable expression of the intestinal markers Mucin 2, Sucrase isomaltase (SI), Villin, Lactase, Trefoil factor 3 (Tff3), Alkaline phosphatase 1(ALP1), or Cryptdin 1 (Fig. 4D) in BME. This confirms the limited effect of Cdx2 overexpression in driving authentic oesophageal epithelial cells to an intestinal columnar phenotype.

2.6. HNF4α induces a columnar-like phenotype in oesophageal explant cultures

We tested the effects of ectopic expression of HNF4α on oesophageal explants cultured in low calcium medium. A transfection efficiency of 96% was achieved with expression of human HNF4α protein was confirmed by immunofluorescence (Fig. 5A). Co-staining for HNF4α and p63 in control and HNF4α infected cultures revealed a reduction in the number of p63-positive cells from 98% in HNF4α-infected cultures to 32% in control infected cultures (n=3; S.D +/- 11.6%) indicating that HNF4α suppresses the SSQE phenotype (Supplementary Fig 3).

In addition we examined expression of the columnar marker cytokeratin 8 (K8) (Yu et al., 2005), E-cadherin and villin (Fig. 5C-E respectively). We found that E-cadherin is not expressed in the low calcium cultures but that it becomes robustly expressed in the presence of HNF4α (Fig. 5D). HNF4α also induces expression of cytokeratin 8 (K8) and villin (Fig. 5C and E). To ascertain whether HNF4α was able to provoke an intestinal columnar phenotype, we determined the expression of Cdx1, Cdx2, Mucin2, SI, Villin, Lactase, Tff3, ALP1, the stomach mucin Muc5AC and K14 by PCR. Villin was robustly expressed following ectopic HNF4α expression, while expression of the transcription factor Tff3 was induced to a lesser extent. All other mRNAs examined were not detected (Fig. 5F).

We also tested the effects of Cdx2 and HNF4α in combination but conditions could not be found in which the cultures remained viable.

2.7. Adenoviral expression of Cdx2, HNF1α and HNF4α in Het-1A cells

Because it was not practicable to test the combined effect of Cdx2 and HNF4α on the oesophageal explant model, for this purpose we used the human Het-1A oesophageal cell line. In these experiments an additional gene, HNF1α, was included. HNF1α plays a crucial role in intestinal development so we wished to determine if co-expression with HNF4α and Cdx2 could further enhance intestinal gene expression. Het1A cells were infected with virus encoding Cdx2, HNF4α and HNF1α alone or in combination and analysed by RT-PCR for the induction of Mucin2, K20, SI and Villin (Fig. 6A). Infection with HNF4α alone induced expression of villin, while Cdx2 provoked the expression of K20 and SI. Combined infection with HNF4α and Cdx2 resulted in the induction of villin, K20 and SI. Infection with HNF1α

Fig. 2. Characterisation of oesophageal explant cultures. (A) Brightfield images of a single mouse oesophageal explant followed over 7 days of culture. An outgrowth of cells is first observed after 2 days of culture (see inset for higher magnification), and increases in size thereafter. Scale bars represent 250 µm. (B) Immunofluorescent staining of oesophageal explants for (i) SMA, (ii) E-cad, (iii) SMA/PanCK (red/green), (iv) K4, (v) K4/K14 (green/red), (vi) SMA/PanCK (red/green), (vii) SMA/K14 (green/red), (viii) K4/K14 (green/red). Z-stack images are shown for clarity (vii, viii and xii). Scale bars represent 500 µm (i/ii), 200 µm (vi), 100 µm (ix), 50 µm (iii/x/xi) and 20 µm (iv/v). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
enhanced Cdx2 induced expression of K20 and SI but had a negligible effect on its own. Interestingly, HNF1α expression appeared to have an antagonistic effect on HNF4α mediated induction of villin.

We also generated stable HNF4α-expressing Het-1A cells (Het-1A-HNF4α c1). Expression of HNF4α protein in the Het-1A-HNF4α c1 clone was confirmed by immunofluorescence (Fig. 6B) and induction of intestinal gene expression analysed by RT-PCR (Fig. 6C). Robust expression of Villin was induced in the stable Het-1A-HNF4α c1 clone. Subsequent infection with Cdx2 induced K20 and SI expression, while HNF1α did not. K20 and SI were induced following combined infection with Cdx2 and HNF1α whereas villin expression was reduced. Quantitative RT-PCR analysis revealed a significant increase in villin expression in HNF4α transiently transfected Het-1A cells and the stable Het-1A-HNF4α c1 clone (compared to uninfected controls) but this was not significantly increased by addition of Cdx2 or HNF1α. There was no significant increase in villin expression in cells infected with the virus combinations tested (Supplementary Fig 4).

3. Discussion

Although BM itself does not arise spontaneously in rodents, there are several murine rodent-based models of the condition (reviewed in (Kapoor et al., 2015)). Moreover, mechanisms underlying gut differentiation are similar in all mammals and the requirements of tissue supply and in vitro culture make it necessary to use an animal model for experimental purposes. We have developed an adult explant culture model that recapitulates the full repertoire of cell types found in the oesophagus (basal, suprabasal and differentiated layers). The presence
of a myofibroblast connective tissue layer beneath the basal cells allows for epithelial-mesenchymal interactions and might help to maintain the oesophageal phenotype in culture and account for the model’s long-term viability. Above the connective tissue layer, the K14-positive basal cells differentiated and expressed the markers involucrin and K4, prior to the formation of the cornified cell envelope in fully mature squames. (Seery and Watt, 2000) Loricrin is a major component of the cornified cell envelope found in terminally differentiated squamous cells and has been demonstrated in epidermal keratinocyte cultures but to date has not been demonstrated in any in vitro oesophageal model (Hohl et al., 1991). Loricrin is located in the epithelial component of the outgrowth demonstrating that all stages of oesophageal squamous cell differentiation are represented. This model of squamous oesophagus allows for the assessment of the effects of ectopic gene expression on squamous differentiation in the context of columnar metaplasia.

We examined the role of calcium in the differentiation of SSQE. Calcium is an essential determinant of epidermal keratinocyte proliferation and differentiation (Hennings and Holbrook, 1983; Hennings et al., 1980). Mouse epidermal keratinocytes cultured in media containing less than 0.1 mM calcium do not stratify, proliferate rapidly and exhibit wide intercellular distances (Hennings and Holbrook, 1983; Hennings et al., 1980). Calcium at concentrations higher than 0.1 mM provoke an increase in stratification, terminal differentiation and cell-cell contacts (Hennings et al., 1980, 1981). We found that oesophageal cells grown under low calcium conditions behave in a similar way with increased proliferation and lack of stratification and differentiation. Increasing the calcium concentration provokes the formation of cell-cell contacts and the appearance of differentiation markers such as K4.

Several lines of evidence have previously suggested that Cdx2 is implicated in the initiation of BM. We tested the ability of Cdx2 to induce the conversion of oesophageal cells to intestinal cells. However, adult oesophageal explant cultures fail to express any intestinal markers following Cdx2 infection despite the fact that we can obtain efficient Cdx2 expression in the K14-expressing cells in both normal and low calcium culture conditions. The only effect, apparent in the monolayer cultures, is a tendency for loss of p63 from Cdx2-expressing cells. Although at first sight a surprising result, it is consistent with other recent studies. Immortalized oesophageal cells require over-expression of the cell-cycle regulator cyclin D1 along with demethylating agents before ectopic Cdx2 expression can provoke the expression of intestinal genes (Kong et al., 2009). Likewise, a transgenic study in which Cdx2 is driven from the K14 promoter, demonstrated lack of intestinal gene expression in the oesophagus (Kong et al., 2011).
The transgenic experiments in which Cdx2 expression in the stomach provoked intestinal development involved initial upregulation of Cdx2 at foetal stages (Silberg et al., 2002; Mutoh et al., 2002), and it has not been established whether Cdx2 overexpression in the adult stomach has the same effect. One reason why Cdx2 might provoke an intestinal phenotype in foetal but not adult stomach is because the proximal half of the rodent foetal stomach is lined by primitive columnar cells. This suggests that conversion to a columnar phenotype could be a prerequisite before induction of a differentiated intestinal phenotype. This consideration led us to examine HNF4α could be a prerequisite before induction of a differentiated intestinal phenotype in foetal but not adult stomach is because the proximal half of the rodent foetal stomach is lined by primitive columnar cells. This suggests that conversion to a columnar phenotype could be a prerequisite before induction of a differentiated intestinal phenotype. This consideration led us to examine HNF4α, which is expressed in stomach but not in oesophagus in early development (Duncan et al., 1994).

We show here for the first time a potential role for HNF4α in the development of the columnar phenotype in BM. When HNF4α is ectopically expressed in oesophageal cells there is a reduction in the number of cells expressing p63 and a robust induction of villin and, to a lesser extent, Tff3. The presence of Tff3 is significant because it is considered as a marker of differentiated goblet cells (Velcich et al., 2002). In low calcium cultures HNF4α also induces E-cadherin expression. The induction of E-cadherin and K8 is in keeping with the role of HNF4α in epithelialisation and tight junction formation. HNF4α can provoke epithelialisation of a dedifferentiated hepatoma cell line (H5) (Spath and Weiss, 1998). HNF4α-null embryos lack E-cadherin expression, adherens junction proteins and exhibit large intracellular gaps (Parviz et al., 2003; Battle et al., 2006). The induction of E-cadherin in HNF4α-transduced cultures may also reflect functional regulation by the transcription factor. E-cadherin is expressed at a higher level in differentiated enterocytes in the villus region compared to the crypt (Escalf et al., 2005).

Although Tff3 was expressed, we did not observe expression of Muc2 with HNF4α. However it is noteworthy that Muc2 expression is minimally altered in Hnf4α null intestine (Garrison et al., 2006). The ability of Hnf4α to induce a partial intestinal phenotype in non-intestinal/non-hepatic cells has also been demonstrated in NIH-3T3 fibroblasts and MIA PaCa-2 pancreatic cell lines. Stably, retrovirally induced Hnf4α expression provoked the induction of apolipoprotein A-IV and villin in both cell lines as well as Tff3 mRNA in fibroblasts (Babeu et al., 2009). The induction of Tff3 and villin mRNA in oesophageal explants in the present study is in keeping with these findings.

While our results do not provide any particular evidence for a role of Hnf1α in the formation of BM, the results presented here show for the first time that HNF4α induces a columnar phenotype with some intestinal features in oesophageal cells (K8, villin and Tff3). The question therefore arises whether HNF4α is also involved in the development of BM. The presence of HNF4α has previously been shown in BM (Piessen et al., 2007), and we have confirmed this by immunostaining of our own human biopsies. Therefore we consider HNF4α induction a prime candidate as an early initiating event in the formation of BM. The results are consistent with the oesophageal epithelium being the cell of origin for BM although cannot exclude other possibilities such as oesophageal glands or multipotent cells left over from embryonic life (Barbera and Fitzgerald, 2010; Wang et al., 2011; Nicholson et al., 2012). Further investigation will be required to establish the cause of HNF4α induction, and whether the HNF4α protein is found in oesophagitis.

4. Materials and methods

All experiments were repeated at least three times.

4.1. Immunohistochemistry of human tissue

Formalin-fixed wax-embedded sections of archival biopsy forceps
specimens of human oesophagus (normal and BM), gastro-oesophageal junction (GOJ), stomach, small intestine and colon were obtained from the Pathology unit at the Royal United Hospital Bath (REC number: 13/YH/0197). Immunohistochemical staining for CDX2 (1:80) and HNF4α (1:80) was carried out using a polymer detection system and DAB label. Briefly, for Cdx2, tissue sections were dewaxed, rehydrated, submerged in a low pH solution (BioGenex Antigen Retrieval Citra Plus Solution), microwaved until boiling and for two minutes thereafter. Sections were heated for a further 15 min in a 99 °C waterbath, allowed to cool for 20 min, transferred to PBS and sequentially treated with 3% peroxide block and BioGenex Power Block for 10 min each. Cdx2 antibody (BioGenex, Mouse) was diluted 1:80 (BioGenex Enhanced Antibody Diluent) and incubated with the sections for 30 min. Sections were heated for a further 15 min in a 99 °C waterbath, allowed to cool for 20 min, transferred to PBS and sequentially treated with 3% peroxide block and BioGenex Power Block for 10 min each. For HNF4α, sections were submerged in Dako EnVision™ Flex Target Retrieval Solution (high pH - diluted according to manufacturer's instructions), microwaved until boiling and microwave simmered for a further 20 min. Slides were allowed to cool for 20 min and transferred to PBS. Sections were rinsed in PBS and blocked for 2 h in 2% Roche blocker followed by sequential treatments with the BioGenex peroxide and blocking solution as above. Hereafter, sections were subjected to the same protocol of antigen labelling and detection as for Cdx2 with HNF4α (Santa Cruz, Rabbit) also being diluted 1:80. Sections were counterstained with Gill’s haematoxylin (Vector Laboratories).

4.2. Culture of adult squamous mouse oesophageal epithelium

All animal experiments were performed in accordance with UK Home Office regulations. Oesophagi were removed from adult CD1 mice following cervical dislocation and dissected in Minimum Essential Medium Eagle (MEM) with Hank’s salts supplemented with 10% FBS (Invitrogen, Paisley, UK), penicillin/streptomycin (50U, Sigma) and 2 mM l-glutamine (all from Sigma-Aldrich, Poole, UK). The oesophagus was cut at the proximal and distal ends to ensure that gastric and buccal mucosa were excluded. It was opened longitudinally and the epithelium stripped from the underlying connective tissue. Each sample of oesophageal epithelium was dissected into approximate 1 mm² sections and the samples from different individual mice were cultured separately. Sections (10–15) of epithelial tissue were then inserted into furrows that had been etched onto plastic coverslips. The coverslips were then placed in a 35 mm tissue culture dish and covered with 1.5 ml of Basal Medium Eagle (BME) with Earle’s salts (Sigma-Aldrich, Poole, UK) supplemented with 20% foetal bovine serum, penicillin/streptomycin (50U, Sigma) and 2 mM l-glutamine.

For culturing oesophageal explants under low calcium conditions, MCDB 153 (Autogen Bioclear, Wiltshire, UK) medium was supplemented with l-glutamine (6 mM), human epidermal growth factor (5 ng/ml), ethanolamine (6.1 μg/ml), α-phosphoethanolamine (14.1 μg/ml), hydrocortisone (0.5 μg/ml) and bovine insulin (5 μg/ml) (all Autogen Bioclear).

4.3. Culture and generation of stable Het-1A cell line

Het-1A cells (ATCC, Middlesex, UK) were maintained in Basal Medium Eagle medium (BME) (Sigma) supplemented with 10% (v/v) foetal bovine serum (Gibco), 2 mM l-glutamine (Sigma) and penicillin/streptomycin (50U, Sigma). Culture medium was replaced every 2 days, and cells were subcultured (1:10) every 5–7 days.

Stable HNF4α expressing Het-1A cells were generated through lentiviral infection with pL-S-Hnf4α-I-EGFP28. Briefly, the lentivirus was prepared by transfecting pl-S-Hnf4α-I-EGFP and the packaging constructs pSV-G, pREV, pGal/Pol/PRE into HEK293T cells (ECACC, Porton Down, U.K). Virus containing medium was harvested 48 h after

![Image](40x145 to 286x737)

**Fig. 6.** Expression of HNF4α and Cdx2 in Het-1A cells induces the expression of intestinal genes. (A) RT-PCR analysis for Cdx2, HNF1α, HNF4α, K20, Mucin2, SI, Villin and β-actin in Het-1A cells transiently infected with Ad-Null, Ad-Cdx2, Ad-HNF4α, Ad-HNF1α virus alone or in combination as indicated. (B) Immunofluorescent staining for HNF4α and phase contrast images of the stable HNF4α-expressing Het-1A clone Hnf4α-c1. (C) RT-PCR analysis (as above) of stable Hnf4α-c1 cells infected with Ad-Null, Ad-Cdx2, Ad-HNF1α alone or in combination as indicated.
transfection, diluted in complete BME medium supplemented with dextran (5 µg/ml) and added to 6.9×10⁴ Het-1A cells for 24 h. Medium was changed every 2 days following infection. Cells were split and seeded onto 96-well plates for single cell colony selection with HNF4α expression being validated by immunofluorescence and RT-PCR.

### 4.4. Immunostaining of explant cultures and mouse oesophageal sections

Fixation and immunostaining of explant cultures or adult mouse oesophageal sections was performed as described previously (Yu et al., 2005). Primary antibodies were obtained and diluted as described in Table 1. Nuclei were stained with 0.1 µg/ml of 4′, 6-diamidino-2-phenylindole (DAPI). Images were either collected on a Leica DMRB fluorescent microscope with a digital camera or a Zeiss LSM 510 confocal microscope. We determined the specificity of antibodies directed against squamous epithelial epitopes by immunohistochemistry on adult mouse oesophageal sections (p63, K14, K4 and loricrin). In addition, we also determined the expression of villin in sections of adult mouse intestine and oesophagus. All oesophageal and intestinal proteins were expressed appropriately (Supplementary Fig 5).

### 4.5. Construction of Cdx2 and Cdx2-VP16 adenoviral vectors

Two viruses were constructed: one with the VP16 transactivation domain from Herpes simplex and one without. The VP16 virus was fused to the 5′ end of the full length mouse Cdx2 cDNA (from Dr Debra Silberg University of Pennsylvania, USA). Cdx2 was subcloned into a VP16-containing plasmid by Clal digestion. The AdEasy expression system (Strategene) was used for adenovirus delivery into cells and explant cultures. Briefly, BglII and XhoI were used for subcloning Cdx2 and VP16-Cdx2 into the pShuttle-IRES-hrGFP construct. The resulting shuttle vectors were then linearized with PmeI and cotransformed into BJ5183 electropocompetent cells with pAdEasy-1, the supercoiled viral DNA plasmid. Recombination was identified by restriction enzyme digestion analysis. The recombinant constructs were then produced in bulk in XL-10 Gold cells. Purified recombinant adenovirus plasmid DNA was digested with PacI to expose its inverted terminal repeat (ITR), and then used to transfect HEK239 cells where deleted viral assembly genes were complemented in vivo.

### 4.6. Expression of transgenes by adenoviral infection

Transgenes were expressed in cultured epithelium and Het-1A cells using first generation, replication defective, recombinant, adenoviral vectors: Ad-null, Ad-RSV-GFP, Ad-CMV-Cdx2-hrGFP, Ad-CMV-VP16-Cdx2-hrGFP, Ad-CMV-HNF4α and Ad-CMV-HNF4α (Martinez-Jimenez et al., 2006). Each explant culture was incubated with 5×10⁷ infectious units of adenoviral vector in 2 ml of complete BME for 12 h. Oesophageal exfoliants grown under low calcium conditions were incubated with 5×10⁷ IU of adenovirus in 2 ml of MCD 153 media (Autogen Bioclear, Wiltshire, UK) for 12 h. Explants were processed for RT-PCR or immunohistochemistry up to 7 days post-infection.

Het-1A cells were exposed to Ad-null, Ad-CMV-HNF4α, Ad-CMV-VP16-Cdx2-IRES-hrGFP and Ad-HNF1α alone or in combination (as indicated) to an MOI of 15 in the presence of dextran (5 µg/ml) for 24 h. Cells were harvested for analysis 4 days post infection.

### 4.7. Reverse transcription and polymerase chain reaction

RNA extraction, 1st strand cDNA synthesis and reverse transcription polymerase chain reaction was performed as described previously. (Li et al., 2007) Annealing temperatures and primer sequences are shown in Table 2. Quantitative real-time RT-PCR (qRT-PCR) was carried out using a LightCycler 1.5, Roche and reagent mix (FastStart SYBR Green Master, Roche). Primer sequences and annealing temperature are shown in Table 2.

### Conflict of interest

The authors disclose no conflict of interest.

---

**Table 1**

<table>
<thead>
<tr>
<th>Primary antibodies used in immunohistochemistry.</th>
<th>Manufacturer</th>
<th>Dilution</th>
<th>Species</th>
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<td>anti-smooth muscle actin</td>
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<td>anti-cytokeratin 4</td>
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<td>anti-Cdx2</td>
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**Table 2**

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<td>ALPI</td>
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<td>TCA GAT CAG CCT GGG T</td>
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<td>SI</td>
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</tr>
</tbody>
</table>

* Denotes primers used for qRT-PCR.
Author contributions

Study concept and design: BC, JMWS, DT. Acquisition of data: BC, LG, ZDB, YC, WYY. Analysis and interpretation of data: BC, LG, ZDB, YC, JMWS, DT. Drafting of the manuscript: BC, LG, ZDB, YC, WMJ, DT. Critical revision of the manuscript for important intellectual content: RJ, MB, MJQ, JMF, SGW, JMWS. Material support: WYY, RJ, MB, LB. Study supervision: JMF, JMWS, SGW, DT.

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Summary statement

To date the molecular mechanisms underlying Barrett’s oesophagus remain unidentified. We provide evidence for a role of the transcription factor HNF4a in the switch from stratified squamous to columnar epithelium.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.dld.2016.11.001.

References


