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Role of the homeodomain transcription factor Bapx1 in mouse distal stomach development

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Abstract

Background & Aims—Expansion and patterning of the endoderm generate a highly ordered, multi-organ digestive system in vertebrate animals. Among distal foregut derivatives, the gastric corpus, antrum, pylorus and duodenum are distinct structures with sharp boundaries. Some homeodomain transcription factors expressed in gut mesenchyme convey positional information required for anterior-posterior patterning of the digestive tract. Barx1, in particular, controls stomach differentiation and morphogenesis. The NK homeobox gene *Bapx1* (*Nkx3-2*) has an established role in skeletal development but its function in the mammalian gut is less clear.

Methods—We generated a *Bapx1*^{Cre} knock-in allele to fate map *Bapx1*-expressing cells and evaluate its function in gastrointestinal development.

Results—*Bapx1*-expressing cells populate the gut mesenchyme with a rostral boundary in the hindstomach, near the junction of the gastric corpus and antrum. Smooth muscle differentiation and distribution of early regional markers are ostensibly normal in *Bapx1*$^{Cre/Cre}$ gut, but there are distinctive morphologic abnormalities near this rostral *Bapx1* domain: the antral segment of the stomach is markedly shortened and the pyloric constriction is lost. Comparison of expression domains

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and examination of stomach phenotypes in single and compound *Barx1* and *Bapx1* mutant mice suggest a hierarchy between these two factors; *Bapx1* expression is lost in the absence of Barx1.

Conclusions—This study reveals the non-redundant requirement for Bapx1 in distal stomach development, places it within a Barx1-dependent pathway, and illustrates the pervasive influence of gut mesenchyme homeobox genes on endoderm differentiation and digestive organogenesis.

Keywords

Gastrointestinal development; stomach; mesoderm; endoderm; Nkx3-2; Bapx1; pyloric sphincter; Barx1; antrum

INTRODUCTION

Mechanisms responsible for organizing the mammalian stomach into fundus, corpus, and antral-pyloric segments are poorly understood. Corpus epithelium typically carries numerous oxyntic and zymogenic cells that produce acid and digestive enzymes, respectively.[1] The distal stomach, which encompasses the antrum and pylorus, lacks these cell lineages but is marked in mouse and man by presence of endocrine cells that secrete gastrin and mucous cells that produce mucin 6.[1] Muscle cells in the outer pylorus create a sphincter that controls passage of food into the duodenum.

The digestive tract differentiates in response to signals from adjacent mesenchyme.[2] Expression of homeobox genes is often segmental along the anterior-posterior axis of the developing gut and may be especially important in relaying rostro-caudal position.[3] Clustered Hox genes, for example, are expressed in the gut in overlapping domains, reminiscent of patterns observed along the skeletal axis;[4, 5] they are implicated in regional identity and in formation of intestinal sphincters and the cecum.[6–10] Homeodomain proteins participate in mesoderm-endoderm signaling.

The homeobox gene *Barx1* is confined to embryonic stomach mesenchyme and required for proper stomach development.[10–13] In its absence the stomach is markedly small, abnormally shaped, lacks a pyloric constriction, shows mixing of cells from different segments, and carries intestinal villi distally.[11, 12] Some homeobox genes regulate fibroblast growth factor (FGF) expression in the hindgut,[10] and overexpression of NKX2.5 in chick embryos inhibits *Wnt5a* and *Bmp4* expression during formation of the hindstomach (gizzard) and pylorus;[14, 15] *Barx1* acts in part by limiting the duration of Wnt signaling in early stomach development.[11, 12] Many other factors that regulate genetic and tissue interactions in stomach development remain unknown.

The homeodomain of mammalian Nkx3-2 (Bapx1) shares ~87% identity with *Drosophila* BAGPIPE, a NK2 sub-family member that specifies gut smooth muscle in flies.[16] Viral misexpression studies in the chicken suggest that *Bapx1* functions in development of the gizzard, a muscular, keratinized structure in the posterior stomach.[15] In mouse embryos, *Bapx1* mRNA appears first in lateral plate mesoderm, adjacent to gut endoderm, around embryonic day (E) 8.5.[17] *Bapx1* knockout mice were therefore predicted to have gut musculature defects, but the intestine in three separate mutant lines is largely intact[18–20] and investigation has centered on *Bapx1's* role in spleen and skeletal development. One group commented on abnormal gastro-duodenal morphology[20] without investigating molecular details. Although the nature and possible reasons for the defect are unknown, *Bapx1* is cited as being required to generate pyloric sphincter muscle.[21]

We created a targeted mouse line that marks *Bapx1*-expressing cells and eliminates gene activity. Here we report that *Bapx1* is necessary for proper antral-pyloric morphogenesis and

development of antral-type epithelium. We also show that Bapx1 expression in the distal stomach requires *Barx1*. These studies reveal a focal requirement for *Bapx1* in hindstomach organogenesis and outline a transcriptional hierarchy in mammalian stomach development.

MATERIALS and METHODS

Mouse gene targeting

A λ-phage clone from a 129/Sv mouse genomic library was provided by Drs. K-I. Yoshiura and J. Murray, University of Iowa. A 3.6-kb BglII-SacII fragment containing 5′ flanking sequences and the first 46 codons of *Bapx1* exon 1 served as the 5′-homology arm; a 1.6-kb SmaI fragment containing codon 112 through the end of exon 2 served as the 3′-homology arm. A PGK-Neo^R cassette and *Cre* recombinase cDNA were inserted in frame with *Bapx1* coding sequence at the SacII restriction site (Fig. 1A). The construct was electroporated into AB2.2 embryonic stem cells. Two targeted cell lines were used to produce chimeras and $Bapx1^{+/Cre}$ mice. For Southern genotyping, the probe was a [α-^{32}P] dCTP-labeled BglII-SacI fragment from the 3′ segment of the gene, which identifies 5-kb and 7.5-kb bands for wild-type and *Cre* knock-in alleles, respectively (Fig. 1B). To demonstrate correct targeting at the 5′ end, we used primers complementary to the Cre insert (CRE3′: GCCGCATAACCAGTGAAACAGCATTGC) and to genomic DNA ~4.5 kb 5′ to the Bapx1 gene (GTTATGAGTGACAGCCTGGGACG) to amplify a 5.7-kb DNA fragment in the targeted allele (Suppl. Fig. 1). Identity of this fragment was confirmed by BglII/ClaI digestion and sequence analysis using internal primers GGTTTCAAAATGAGGCTC and CATGTATGAATGTGTGGAACCTGG. For subsequent genotyping we used CRE3′ along with CTCGTTCTCTTCGCTCAGGGCTGAG and CCAGGCGATCCTCAACAAGAAGAGGG in a coupled PCR reaction with a 56°C annealing step (Fig. 1C). *Bapx1* targeted mice were maintained on the C57BL/6 background.

Expression analyses

β-galactosidase activity was determined on whole-mount preparations using published methods.[22] For histology, embryos were embedded in paraffin, sectioned at 5 μm, and stained with hematoxylin and eosin. $Bapx1^{Cre/+}$ and $Barx1^{+/-}$ mice were intercrossed to obtain compound homozygotes. Organs from crosses with *Nkx2.5-GFP* transgenic mice, described previously[23], were visualized under a Leica MZ FLIII fluorescent dissecting microscope.

RNA was reverse transcribed using SuperScript™ (Invitrogen). cDNA was detected by PCR using *Bapx1* primers agatgtcagccagcgtttc and gcagaggcgagcaggtcggc. Fetal stomach lysates were resolved by SDS-PAGE. Binding of Bapx1 mouse antiserum H00000579-A01 (Abnova, 1:500) was detected with horseradish peroxidase (HRP)-conjugated goat anti-mouse Ab.

Embryos were fixed overnight in 4% paraformaldehyde at 4°C. 8-μm thick paraffin sections were dried, deparaffinized in xylenes, and rehydrated. For antigen retrieval, slides were immersed in 10 mM sodium citrate, pH 6.0, and treated in a pressure cooker for 2 minutes at 15 psi. Endogenous peroxidase activity was blocked with 3% H_2O_2 in methanol for 15 min and non-specific antibody (Ab) binding with 5% Fetal Bovine Serum for 1 h at 25°C. Primary Ab: SMαA (Sigma A2547 (1A4), 1:1000), PGP9.5 (Chemicon AB1761, 1:2500), H/K-ATPase (D032-3; MBL International; Woburn, MA; 1:1000), intrinsic factor (gift from Dr. D. Alpers, Washington University; St. Louis, MO; 1:24,000), Pdx1, (1:6000, gift of Dr. C. Wright, Vanderbilt University, TN), BMP4, (1:300, Chemicon MAB1049), Nkx 2.5 (1:200, SC14033, Santa Cruz), were applied for 3 h at 25°C or overnight at 4°C. After treating with anti-mouse or anti-rabbit IgG (Jackson ImmunoResearch), then avidin-biotin complex solution (Vector Laboratories) for 1 h at 25°C, color reactions were developed in 0.05% 3,3′-diaminobenzidine

and 0.1% H_2O_2. Slides were counterstained with hematoxylin. Alcian blue staining was by standard methods.

For in situ hybridization, tissues were fixed in 4% paraformaldehyde (Sigma-Aldrich), dehydrated, embedded in paraffin, and sectioned at 6-μm thickness. Deparaffinized, rehydrated sections were treated with Proteinase K (Roche) and 0.1M triethanolamine before hybridization with probes generously provided by T. Lufkin (*Bapx1*), A. McMahon (*Ihh*), and R. Harvey (*Nkx2.5*). After overnight hybridization at 63°C, slides were washed for 2 h in decreasing concentrations of SSC from 2X to 0.2X at 63 °C, then incubated in 5% serum in PBS followed by digoxigenin Ab (Roche; 1:2000) at 4° C overnight. Slides were equilibrated in 100 mM NaCL; 100 mM Tris, pH 9.5; 50 mM $MgCl_2$ and stained (NBT/BCIP tablets, Roche) for 2–4 h.

For expression arrays, RNA was extracted from the distal stomach of E18.5 *Bapx1*$^{Cre/Cre}$ embryos and wild-type littermates using the RNeasy kit (Qiagen). After confirmation of RNA quality, samples were processed and hybridized to Codelink mouse bioarrays (Amersham Biosciences). Raw data were normalized on a $\log_2$ scale and filtered to reduce noise. Differential gene expression and functional gene groupings were analyzed using MatchMiner (http://discover.nci.nih.gov/matchminer/), GoMiner (http://discover.nci.nih.gov/gominer/) and GeneSpring (Agilent Technologies) software and are deposited in the GEO database (acc. # _____).

RESULTS

Tracing Bapx1 expression

We used homologous recombination to replace *Bapx1* at codon 46 (exon 1) with in-frame *Cre* cDNA (*Bapx1*^{Cre}, Fig. 1A). Two independent mutant lines showed evidence for correct gene targeting (Fig. 1B,C) loss of *Bapx1* mRNA (Fig. 1D), and no material effect on expression of the two flanking genes (Suppl. Fig 1C). We crossed these mice with *ROSA26* reporter mice, where a floxed translation-stop sequence restricts *LacZ* gene expression to Cre-expressing cells and their progeny.[24] β-galactosidase (β-gal/LacZ) activity first appeared in *Bapx1*^{Cre};*ROSA26R* embryos at E9.5 in gut mesoderm and weakly in somites (Fig. 2A,B; data not shown). Between E10.5 and E12.5, β-gal activity was prominent in the splanchnic mesoderm, somites, calvarium, Meckel's cartilage, and spleen anlage (Figs. 1E, 2C–D, Suppl. Fig. 2A–G). By E13.5 *Bapx1* expression was evident in the cardiac outflow tract (Fig. 1F) and condensing cartilage of the ribs, skull (Suppl. Fig. 2I–N), and long bones. Staining in the digestive tract was confined to mesodermal derivatives and excluded from endoderm at all stages (Figs. 1G and 2E,F). These findings agree with previous reports of *Bapx1*'s role in developing skeleton and spleen[17–20] and establish the fidelity of *Bapx1*^{Cre} mice to mark *Bapx1*-expressing cells and elucidate *Bapx1* function in other organs.

Definition of gene expression along the long axis of the embryonic stomach is confounded by rotation of the organ, from an initial lie parallel to the body's anterior-posterior axis to a final position that is nearly perpendicular. We examined serial embryo sections with the attention required to distinguish the stomach's antero-posterior and radial axes. LacZ expression in *Bapx1*$^{Cre/+}$ embryonic gut initiated in the distal stomach. Staining at E10.5 was intense in the caudal foregut and stomach-intestine junction but absent from the rostral foregut and stomach (Fig. 2E, sections from the same embryo in a rostral to caudal series). At E11.5, expression remained evident in the hindstomach but faint or absent in forestomach (Fig. 2F), extended into the full length of intestine, and included the spleen anlage (Fig. 2F). LacZ staining involved all cells in the full thickness of the mesenchyme (Suppl. Fig. 3). In older embryos, β-gal activity was present in much of the stomach, with a persistent caudal-to-rostral gradient (data not shown).

Early chick embryos express *Bapx1* in the prospective gizzard (posterior stomach) but not the proventriculus (anterior stomach).[15] Our Cre-based lineage analysis in mice confirmed *Bapx1* expression in tissues with known functions and disclosed an anterior boundary previously unappreciated in mammalian stomach. The rostral limit of earliest *Bapx1* expression corresponds roughly to the junction between corpus and antrum.

Abnormal stomach development in Bapx1^{Cre} homozygotes

Crosses between *Bapx1*$^{+/Cre}$ mice yielded null mutants in Mendelian proportions until E18.5 (25.6% *Bapx1*$^{+/+}$, 48% *Bapx1*$^{Cre/+}$ and 26.4% *Bapx1*$^{Cre/Cre}$). Mutant homozygotes typically died 1 to 3 days after birth, and ~90% of weanlings were wild-type or heterozygote. Perinatal lethality, similar to that reported with other Bapx1-null alleles,[17–20] likely reflects skeletal malformation (Suppl. Fig. 2O,P). The spleen was absent or markedly hypoplastic in *Bapx1*$^{Cre/Cre}$ mice, as judged grossly (Fig. 3B) and by expression of a Nkx2.5-GFP transgene (Suppl. Fig. 4), a marker of the developing spleen.[12, 25]

Bapx1$^{Cre/Cre}$ stomachs were modestly reduced in size. Nearly all of this reduction occurred in the distal segment, which was also dilated and lacked constriction at the gastro-duodenal junction, the site of the pyloric sphincter (Fig. 3A,B). Histologic examination confirmed distal dilatation and revealed severe shortening of the antral-pyloric segment (Fig. 3C,D). Expression and distribution of PGP9.5, an enteric nervous system marker,[26, 27] and smooth-muscle α-actin were intact (Fig. 3E–H).

Epithelia in the gastric body and antrum have distinctive features. Specialized, Alcian blue-avid mucous cells found at the base of antral gland units are normally absent from the corpus; conversely, the antrum lacks chief and oxyntic cells, the dominant lineages in the body.[1] Normal hindstomach hence corresponds to the Alcian blue-staining region between the zone of chief and parietal cells in the corpus and the villous duodenal epithelium (Suppl. Fig. 5A). *Bapx1*$^{Cre/Cre}$ stomachs carried few, and in many cases, no glandular units with basal Alcian blue avidity (Fig. 4A,E *vs* 4B,F), whereas intestinal goblet cells stained readily with Alcian blue (Fig. 4F). Additionally, the distance between H/K-ATPase- (Fig. 4C,G *vs* 4D,H) or gastric intrinsic factor- (GIF, Suppl. Fig. 5B–E) expressing cells in the stomach body and the villous intestinal epithelium was markedly reduced. These corpus lineage markers frequently abutted the intestine (Fig. 4H, Suppl. Fig. 5E), indicating diminution or loss of mature antral character. Scrutiny of Alcian blue, H/K-ATPase, and GIF stains revealed normal cell composition in distal corpus glands and absence of mixed corpus-antral units (Suppl. Fig. 5F).

Thus, absence of Bapx1 leads to significant hindstomach truncation and loss of the pyloric constriction. The normal appearance of gastric smooth muscle (Fig. 3H) and ostensibly normal intestine and gastric corpus point to a localized defect in antral-pyloric development. Although histologic examination sometimes gave the impression that antral hypoplasia was more severe along the lesser than the greater curvature of the stomach (e.g., Fig. 4C,D), most samples lacked such disparity (e.g., Fig. 3C,D, Suppl. Fig. 6B), which we attribute to subtle variation in tissue orientation. Indeed, objective quantitation of multiple samples confirmed that both aspects of the antrum were affected (Suppl. Fig. 6A).

Molecular correlates of Bapx1 in hindstomach development

Indian Hedgehog (*Ihh*) mRNA is enriched in fetal mouse corpus and antrum, whereas *Sonic hedgehog* (*Shh*) is enriched in the forestomach.[28] In a sign that early patterning is preserved in *Bapx1*$^{Cre/Cre}$ stomach, the boundaries of *Ihh* (Fig. 5A,B) and *Shh* (data not shown) expression were intact at E11.5. Expression of the homeobox gene *Pdx1* is normally limited to the antral-pyloric segment, providing a reliable marker of this stomach region.[29] Pdx1 expression also was similar in *Bapx1*$^{Cre/Cre}$ and wild-type stomach early in development

(E11.5 and E14.5 shown in Fig. 5C–F). Consistent with the observation of antral hypoplasia, the *Pdx1* expression domain was substantially smaller at E18.5 (data not shown). However, the typical transition in staining pattern between antrum and corpus, and the symmetry across greater and lesser curvatures, were preserved. Antral hypoplasia in the absence of Bapx1 hence occurs on the background of correct anterior-posterior stomach patterning.

In chick embryos, *Nkx2.5* and *Bapx1* are expressed in the distal stomach (gizzard), while *Bmp4* and *Wnt5a* appear in the proximal proventriculus and are excluded from the gizzard.[15, 30] Nkx2.5 may regulate pyloric sphincter development, and forced Bapx1 expression in the proventriculus inhibits endogenous *Bmp4* expression.[15] In mouse embryos, by contrast, we observed *Bmp4* expression throughout stomach and intestinal mesenchyme (data not shown); Nkx2.5 mRNA and protein were also expressed widely in mesoderm at the gastroduodenal junction but clearly enriched in pyloric sphincter muscle, as predicted (Fig. 5G and Suppl. Fig. 2). Levels and distribution of both Nkx2.5 (Fig. 5H, Suppl. Fig. 4) and Bmp4 (data not shown) were unaltered in *Bapx1*$^{Cre/Cre}$ stomach, indicating that Bapx1 loss does not interfere with their expression.

Next we surveyed changes in *Bapx1*$^{Cre/Cre}$ antral gene expression, using microarray analysis followed by qRT-PCR confirmation of representative results (data not shown). As early stomach pattern seems intact, we reasoned that antra from older embryos would better reveal aberrant gene expression. The distal stomach in *Bapx1*$^{Cre/Cre}$ embryos at E18.5 showed an increase in corpus-specific *H/K-ATPase* and *Gif* transcripts and a corresponding decrease in antrum-specific *Muc6* mRNA (Suppl. Table 1A). These changes are consistent with the loss of antral, and distal extension of corpus, character. Considering functional gene classes (Gene Ontology), we noted increased expression of transcripts in groups related to epithelial-mesenchymal transition and regulation of endocytosis, whereas groups associated with Smad proteins, nuclear protein import, and vesicle membranes were expressed at lower levels (Suppl. Table 1B). These molecular changes in distal *Bapx1*$^{Cre/Cre}$ stomach represent an unknown combination of additional regional markers and possible underpinnings of antral hypoplasia.

Bapx1 may function downstream of Barx1 to mediate antral-pyloric development

Bapx1 is co-expressed in embryonic hindstomach mesenchyme with *Barx1*, although the domain of *Barx1* expression encompasses nearly the whole stomach (Fig. 6A). Both genes influence differentiation of overlying stomach endoderm and formation of the pyloric sphincter; the antral segment is abbreviated in *Bapx1*$^{Cre/Cre}$ mice (Figs. 3,4) and likely lost in *Barx1*$^{-/-}$ mice.[12] We crossed mice to produce compound homozygote mutants, which we studied immediately after birth because *Barx1*$^{-/-}$ mice die of respiratory failure in the perinatal period.[12] Stomach anomalies in *Barx1*$^{-/-}$; *Bapx1*$^{Cre/Cre}$ and *Barx1*$^{-/-}$;*Bapx1*$^{+/+}$ neonates were identical (Fig. 6B,C); there was no worsening of the isolated *Barx1* mutant phenotype, which is more severe than the *Bapx1*$^{Cre/Cre}$ antral defect.

To further evaluate the relationship between these co-expressed factors, we investigated gene expression in each individual knockout strain. Levels and distribution of *Barx1* mRNA were not reduced or altered in fetal *Bapx1*$^{Cre/Cre}$ stomachs and may even increase slightly (Fig. 6D–E, Suppl. Table 1A). Thus, Barx1 does not require *Bapx1* for its expression and acts either upstream or independent of Bapx1. Conversely, we detected *Bapx1* transcripts in wild-type hindstomach and spleen (Fig. 6F, arrow and arrowhead) but not in the caudal *Barx1*$^{-/-}$ stomach (Fig. 6G, arrow), indicating that hindstomach *Bapx1* expression requires Barx1 function. *Bapx1* expression was equally robust in wild-type and *Barx1*$^{-/-}$ somites (Fig. 6G inset), ruling out trivial reasons for lack of a stomach signal. Quantitative RT-PCR and immunoblot analyses confirmed that *Bapx1* mRNA levels were markedly reduced or absent in *Barx1*$^{-/-}$ stomachs (Fig. 6H,I). These observations collectively suggest that *Bapx1* expression depends on

Barx1 and that antral dysmorphogenesis in *Barx1*$^{-/-}$ stomachs might potentially reflect the attendant *Bapx1* deficiency.

DISCUSSION

Organogenesis requires positional cues to specify cell and tissue types correctly. Homeobox genes play a vital role in regulating developmental processes and imparting positional identity.[31, 32] We used homologous recombination to drive Cre expression from the mouse *Bapx1* locus, thus creating a new null allele to define expression and study gene function in the developing gut. *Bapx1*$^{+/Cre}$;*ROSA26R* mice confirmed *Bapx1* expression domains reported previously in cartilage and spleen and revealed that early in digestive tract development, *Bapx1*-expressing cells and their progeny are confined to the intestine and prospective hindstomach. In line with this observation, *Bapx1*$^{Cre/Cre}$ mice show significant shortening of the antral segment and virtual apposition of the gastric body to the duodenum. Pdx1 and *Ihh*, two posterior markers, show correct regional expression, implying that certain elements of early stomach patterning are preserved. Thus, *Bapx1*$^{Cre/Cre}$ hindstomach defects seem to reflect a failure of proper expansion and morphogenesis of the antral-pyloric segment. As the affected region corresponds to that where Bapx1 expression initiates in the digestive tract, we infer that Bapx1 activity is uniquely responsible for these aspects, even if the precise molecular mechanism is presently unknown.

Despite ostensibly normal smooth muscle differentiation and preserved expression of *Nkx2.5*, a gene implicated in chick gizzard development,[33] *Bapx1*$^{Cre/Cre}$ mice also lack normal pylorus morphology. Mice deleted for nearly the full *Hoxd* gene cluster lose multiple gastrointestinal valves, including the pyloric sphincter, with associated changes in regional smooth muscle and mucosa;[9] the pyloric constriction is also missing in *Barx1*$^{-/-}$ mice.[12] These findings may be relevant to hypertrophic pyloric stenosis, a common congenital disorder.[34] Future efforts should aim to understand how these homeobox genes interact to generate the pyloric sphincter.

The stomach corpus and intestine developed normally, indicating that the antrum-pylorus is the only gut segment that requires *Bapx1* for proper development. Alternatively, *Bapx1* may function redundantly with other homeobox genes elsewhere. Less likely, abnormal hindstomach development could reflect dysmorphogenesis of the spleen and pancreas. Around E8.5 in mouse development, Bapx1 mediates lateral growth of the splanchnic mesodermal plate and coupled leftward growth of the dorsal pancreas, associated with control of *Fgf10* expression.[35] However, anomalies akin to those we identify in *Bapx1*$^{Cre/Cre}$ stomach are not seen with a wide range of defects in spleen and pancreas development.[12, 25] In chondrocytes, Bapx1 serves both proliferative and anti-apoptotic roles,[19, 36] and one reason the antrum and pylorus may develop aberrantly in its absence is if hindstomach progenitors are disadvantaged relative to anterior cells programmed for corpus differentiation. Immunostaining for cleaved caspase 3 did not reveal excess apoptosis in E11.5 hindstomachs (data not shown).

Forced Bapx1 expression in the chick proventriculus (forestomach) suppresses *Bmp4* and *Wnt5a* expression and region-specific differentiation; conversely, forced expression of Bapx1-VP16, which artificially converts a presumed repressor into a transcriptional activator, promotes occasional expression of BMP4 and *Wnt5a* in the gizzard.[15, 37] By contrast, *Bmp4* expression does not appear to be compartmentalized in the mammalian stomach, nor did we detect aberrant expression of *Bmp4* or *Nkx2.1* in the mutant organ. Thus, despite similarities in *Bapx1* expression and function in developing posterior stomach, phenotypes and affected pathways in chick and mouse seem different. These could reflect different mechanisms to create the keratinized avian gizzard versus the glandular mammalian antrum.

Although *Barx1* and *Bapx1* appear in different compartments in the developing spleen and their mutant phenotypes in that organ are distinct,[12, 18, 19, 21, 38] their expression in distal stomach mesenchyme is overlapping. Absence of Barx1 markedly disrupts stomach development, producing aberrant morphogenesis, intestinal homeosis, and pyloric sphincter agenesis. Additional loss of Bapx1 does not worsen this phenotype, and the greater severity of antral- pyloric defects in the *Barx1* mutant hints at actions upstream of *Bapx1*. Indeed, *Bapx1* expression is virtually lost in *Barx1*-null stomach and its absence could potentially account for some part of the $Barx1^{-/-}$ phenotype in the distal organ. Mice with tissue-specific loss of a third stomach transcription factor, the nuclear hormone receptor COUP-TFII, also show a mild patterning defect.[39] Besides expansion and disorganization of circular smooth muscle and enteric neurons, the margin between forestomach and corpus is shifted anteriorly and the glandular stomach accordingly occupies a larger relative space. Although expansion of the corpus is a common feature of the two phenotypes, they occur at opposite ends, anteriorly in the case of COUP-TFII deficiency and posteriorly in $Bapx1^{Cre/Cre}$ animals.

Barx1 is expressed throughout stomach mesenchyme, whereas *Bapx1* is initially confined to the caudal region. Thus, although Barx1 seems to be required for stomach *Bapx1* expression, it cannot be sufficient to restrict expression to the hindstomach; other factors may promote *Bapx1* expression caudally or repress it rostrally. We are presently investigating Barx1's role in *COUP-TFII* expression. Our results meanwhile implicate *Barx1* and *Bapx1* within an essential pathway for mammalian hindstomach development.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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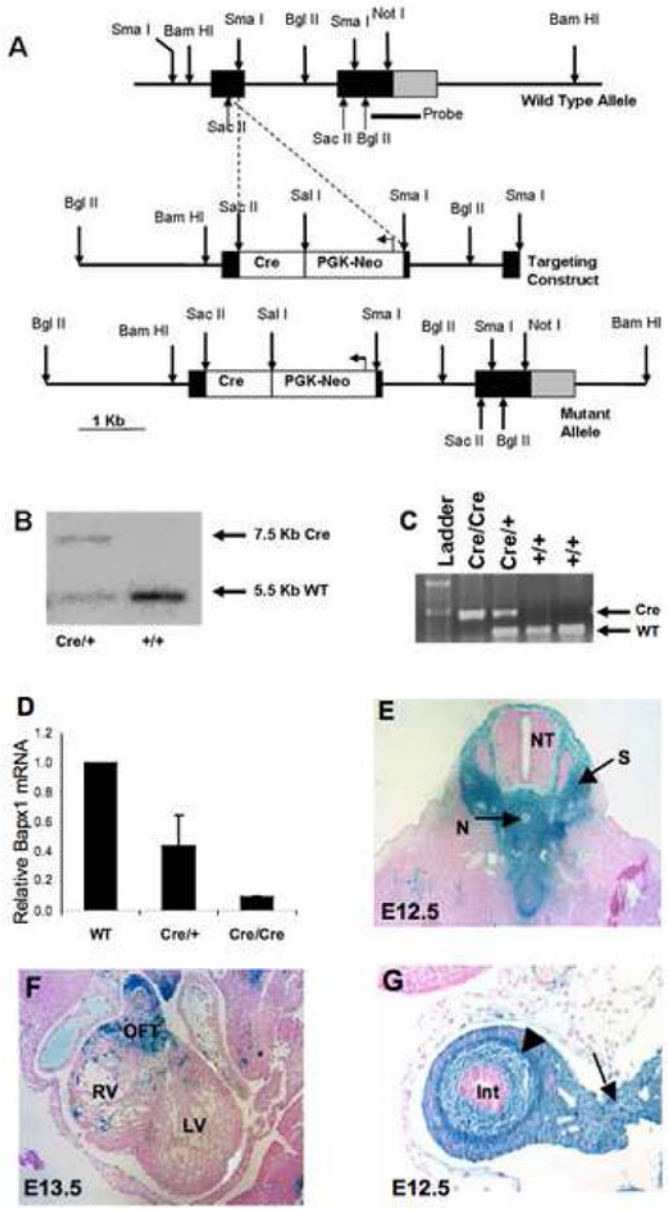

Figure 1. Generation of Bapx1^{Cre} targeted mice and their application to examine *Bapx1* gene expression

(A) Molecular strategy to generate ES cells with Cre recombinase targeted to the first *Bapx1* exon between the *SacII* and *SmaI* sites. **(B)** Mice were genotyped by Southern hybridization using probes corresponding to the 3′ half of exon 2 and part of the 3′ untranslated region. Subsequent generations were genotyped by PCR **(C). (D)** Confirmation that Bapx1 expression is extinguished in *Bapx1*$^{Cre/Cre}$ mice. qRT-PCR on fetal and newborn tibial RNA, expressing *Bapx1* mRNA content relative to *Gapdh* mRNA in wild-type (WT, *n*=10), *Bapx1*$^{Cre/+}$ (HET, *n*=14) and *Bapx1*$^{Cre/Cre}$ (KO, *n*=10) samples. **(E–G)** *Bapx1*$^{Cre/+}$ mice were crossed with the *ROSA26R* reporter strain and progeny were examined for Cre-expressing cells and their descendants by β-galactosidase activity. In E12.5 embryos, staining was detected in sites of documented *Bapx1* expression or function, including condensing vertebrae (**E**) and gut mesenchyme (arrowhead) and mesentery (arrow) (**G**). Staining also appeared in E13.5 cardiac

outflow tract (**F**) and, later, throughout the developing skeleton (see Suppl. Fig. 1). OFT, cardiac outflow tract; RV, right ventricle; LV, left ventricle; CC, central canal; NT, neural tube; N, notochord; S, sclerotome.

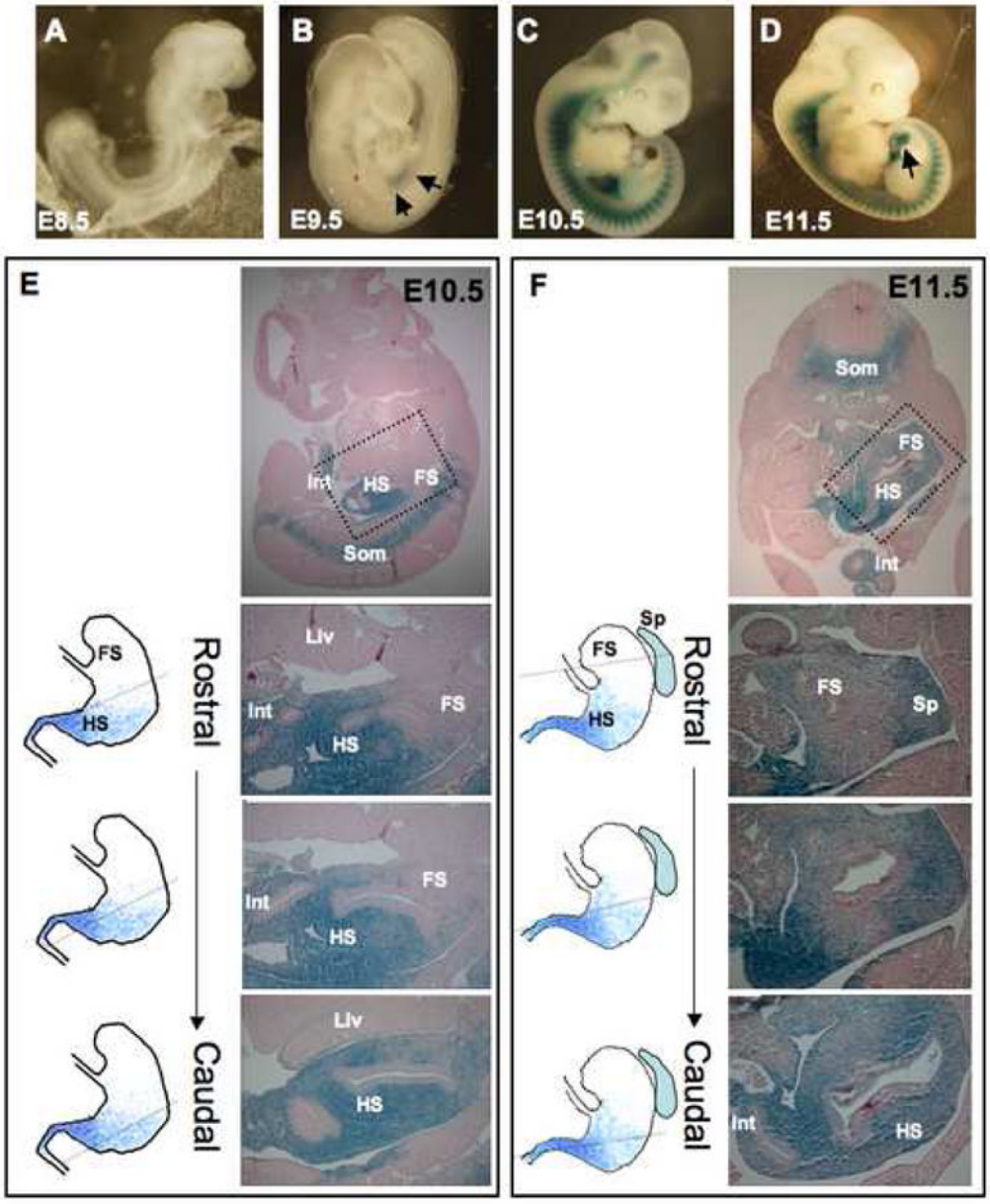

Figure 2. Lineage mapping in *Bapx1*^{Cre} mice reveals a rostral boundary of *Bapx1* gene expression in embryonic hindstomach

(A–D) Whole-mount *LacZ* staining of *Bapx1*$^{Cre/+}$*; ROSA26R* embryos identifies *Cre*-expressing cells and their descendants. Staining is not apparent through E8.5 (**A**) and first appears near the stomach-intestine boundary by E9.5 (**B**, arrows). By E10.5, *LacZ* activity is evident in all anterior somites and in gut and craniofacial mesenchyme (**C**). Expression is readily apparent in mesenchyme of herniated E11.5 intestine (**D**, arrow). **(E,F)** Microscopic examination exposes a rostral limit of *LacZ* activity in the hindstomach at E10.5 (**E**) and E11.5 (**F**): intestine (Int) and hindstomach (HS) are stained strongly, whereas forestomach (FS) activity is much reduced or absent. Som, somites; Liv, liver; Sp, spleen. Sections from embryos at each stage are arranged in rostral to caudal sequence from areas corresponding to those outlined by dotted boxes. Rostral sections show minimal LacZ activity in the forestomach compared to the caudal (hindstomach) tissue or spleen (Sp). Schemas for the domain of

Bapx1 gene expression in relation to stomach and spleen anatomy are depicted next to each section, with a dotted line indicating the approximate plane of section.

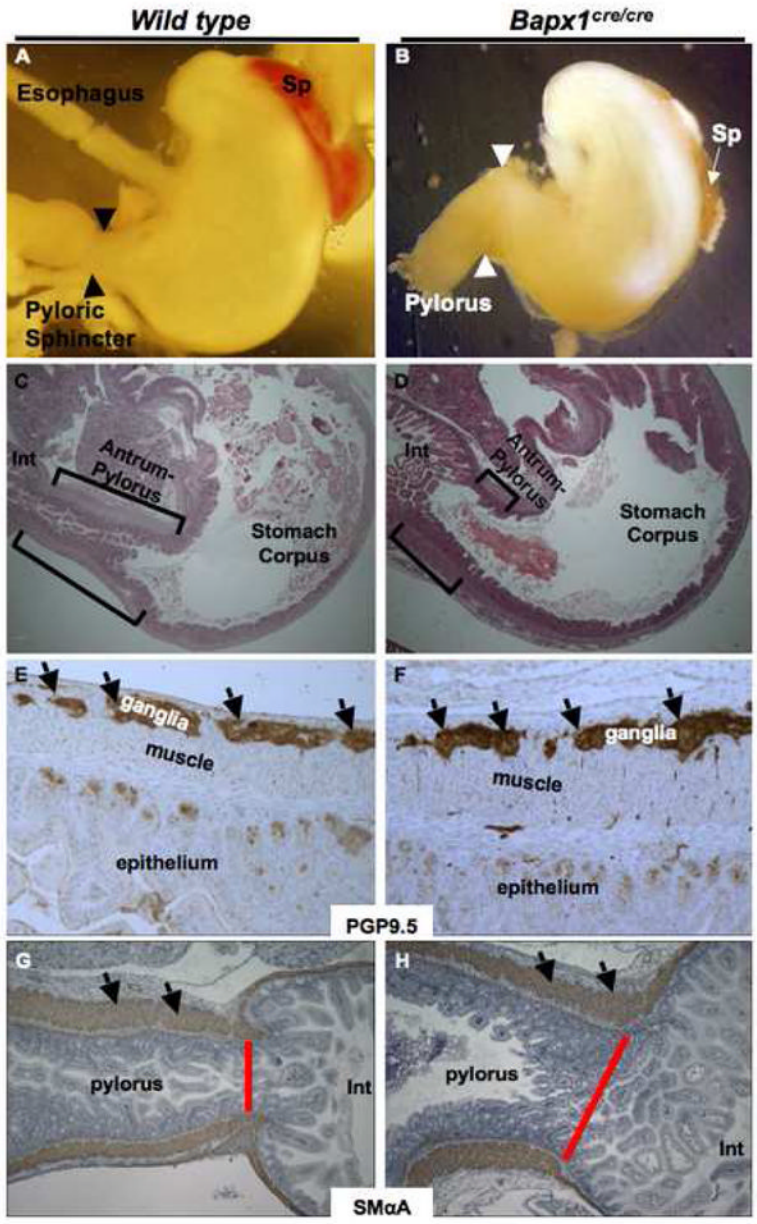

Figure 3. Stomach development in the absence of Bapx1 function

(A–D) Gross and microscopic evidence for hindstomach defects in *Bapx1*$^{Cre/Cre}$ mice. Whole-mount views (**A,B**) and hematoxylin/eosin-stained histologic sections (**C,D**) of E16.5 and neonatal specimens, respectively. Marked truncation of the antral-pyloric segment of the stomach (brackets) and lack of the pyloric constriction (arrowheads) are readily evident. The spleen (Sp) is also absent or markedly hypoplastic in *Bapx1*$^{cre/cre}$ mice. (**E–H**) Immunohistochemical analysis of PGP9.5 (**E,F**) and smooth muscle α-actin (**G,H**) in *Bapx1*$^{cre/cre}$ neonatal hindstomach indicates ostensibly intact enteric nerve and smooth muscle differentiation, respectively. Arrows point to immunostaining of ganglia (**E,F**) or smooth muscle (**G,H**). Red bars demarcate the pylorus and highlight the marked difference in width between control and mutant samples.

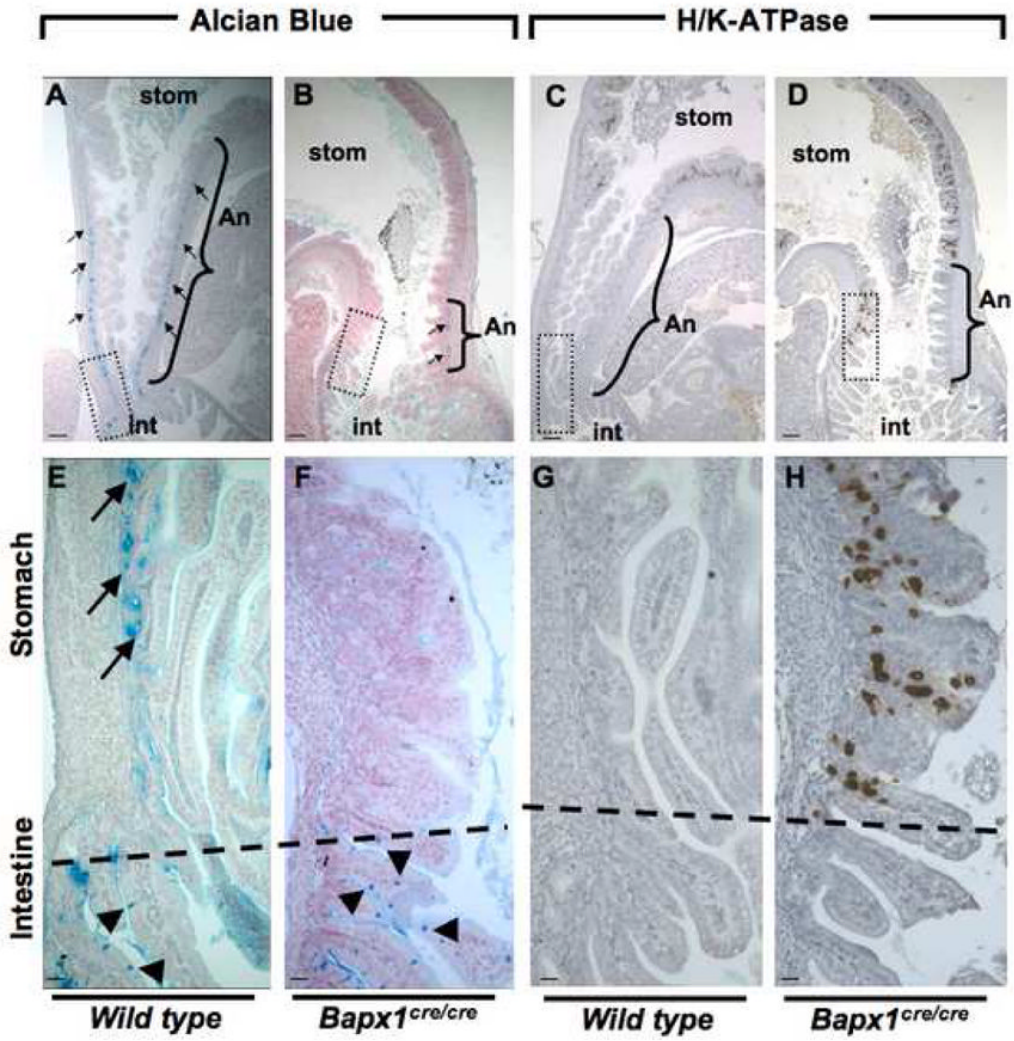

Figure 4. Regional markers verify hindstomach epithelial defects in *Bapx1*$^{Cre/Cre}$ mice

Critical examination of antral Alcian blue staining and of the gastric corpus marker H/K-ATPase. **(A–D)** Low-power microscopic views of the gastro-duodenal junction in wild-type (**A,C**) and *Bapx1*$^{Cre/Cre}$ (**B,D**) neonates. Brackets mark the region expressing antral-pyloric markers along the greater curvature (An, antrum-pylorus), separating the stomach (stom) corpus from intestine (int). Boxes outline regions of the gastro-duodenal junction shown at higher magnification in panels **E–H**. Alcian blue staining in mutant antral epithelium, which marks characteristic mucous cells at the gland base (arrows) in wild-type mice (**A,E**), is significantly reduced along the greater curvature and missing from the lesser curvature. Intestinal goblet cells (arrowheads), which also stain with Alcian Blue, are unaffected. Conversely, H/K-ATPase immunostaining marks parietal cells in wild-type gastric corpus and is absent from normal antral-pyloric mucosa (**C,G**). In *Bapx1*$^{Cre/Cre}$ mice, H/K-ATPase-expressing cells reside immediately adjacent to the intestine (**D,H**), again disclosing loss of antral mucosa. Similarly, expression of Intrinsic Factor, a marker of corpus-resident zymogenic cells, abuts the intestine along the lesser curvature and comes close to the intestine along the greater curvature in *Bapx1*$^{Cre/Cre}$ stomach (Suppl. Fig. 3). Bars A–D, 300um; E–H, 60um.

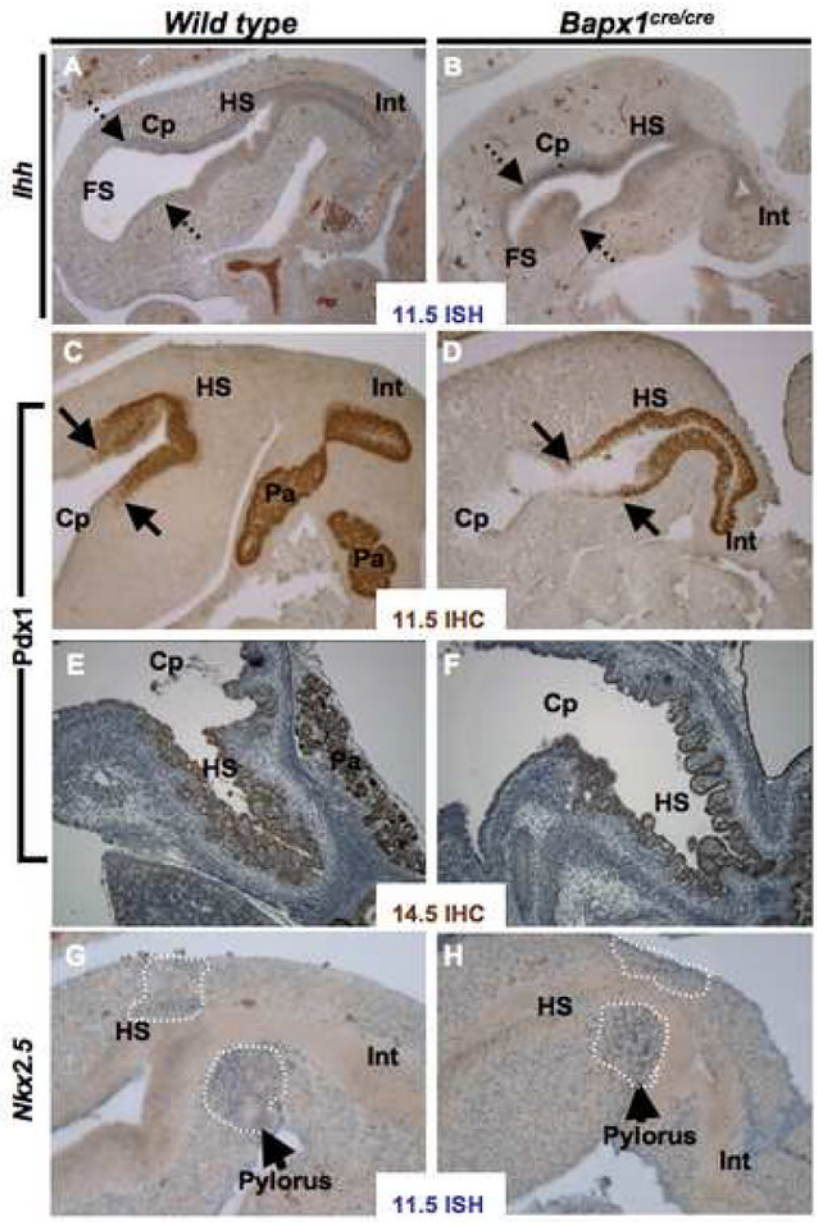

Figure 5. Molecular correlates of embryonic stomach pattern and pylorus development imply normal patterning early in *Bapx1*$^{Cre/Cre}$ stomach development

(A–F) Markers of hindstomach endoderm, *Ihh* mRNA (**A,B**) and Pdx1 protein (**C–F**), showed no difference in expression between wild-type and *Bapx1*$^{Cre/Cre}$ stomachs at E11.5 (**A–D**) or E14.5 (**E,F**). Dashed arrows mark the rostral limit of *Ihh* expression, which is much stronger in hindstomach (HS) and corpus (Cp) compared to forestomach (FS); solid arrows mark the anterior boundary of PDX1 expression, at the corpus-antral junction. PDX1 is also expressed in proximal intestine (Int) and pancreas (Pa), as seen especially clearly in the control samples (**C,E**). **(G–H)** Expression of the chick hindstomach and pyloric determinant Nkx2.5 mRNA in *Bapx1*$^{Cre/Cre}$ and wild-type stomachs at E11.5. Nkx2.5 expression, which marks developing pyloric sphincter muscle (arrows, dashed lines), was unaffected by Bapx1 loss. Similar results were observed by immunostaining (E14.5, data not shown). ISH, *in situ* hybridization; IHC, immunohistochemistry.

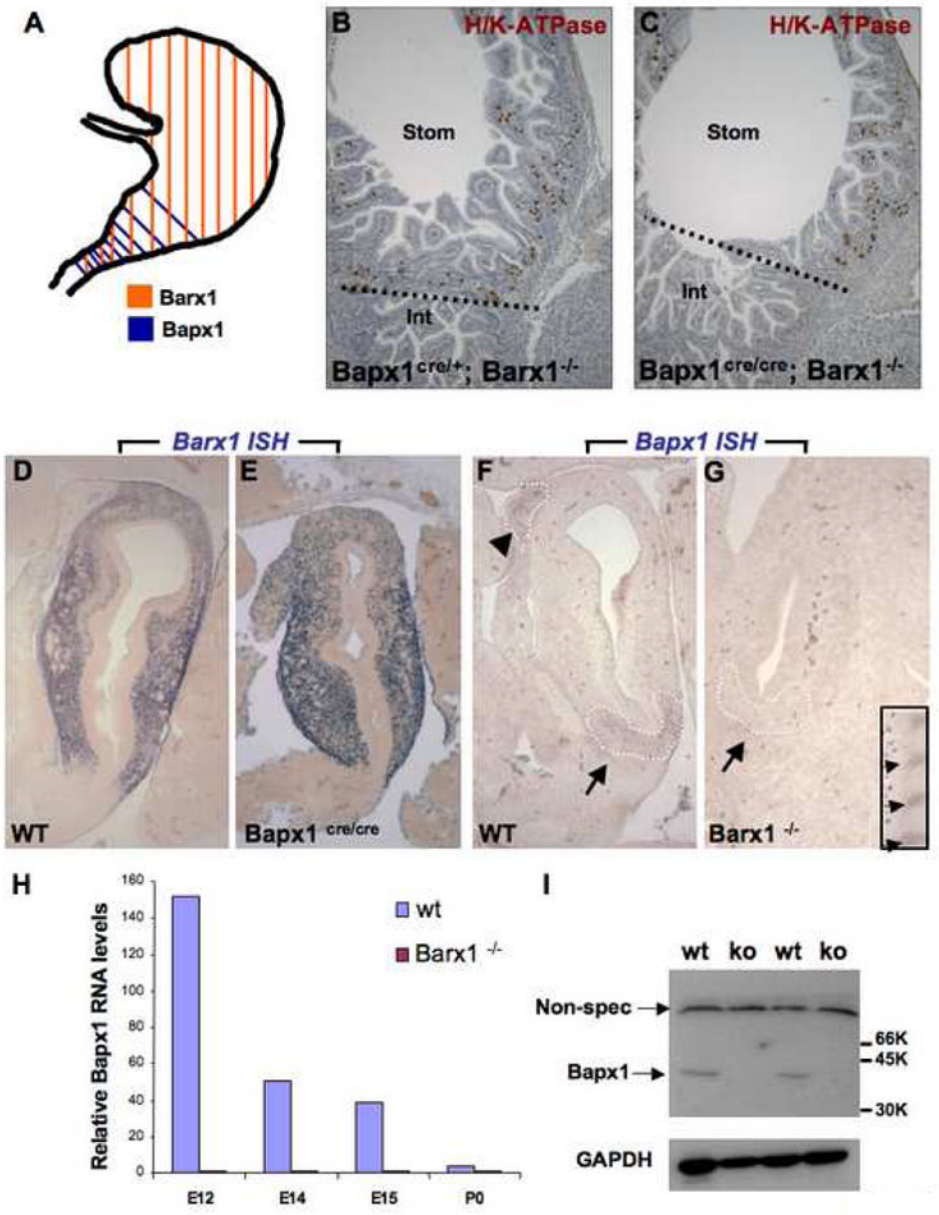

Figure 6. Barx1 may function upstream of Bapx1 to control antral-pyloric development

(A) Schematic depiction of *Barx1* and *Bapx1* expression in mid-gestation mouse stomach mesenchyme. Early *Bapx1* expression is restricted to the antrum and pylorus (blue) and overlaps with *Barx1* expression, which extends throughout the stomach (orange). **(B,C)** Further loss of Bapx1 does not worsen the stomach phenotype in $Barx1^{-/-}$ mice. Stomachs from $Barx1^{-/-}$; $Bapx1^{Cre/+}$ (**B**) and $Barx1^{-/-}$;$Bapx1^{Cre/Cre}$ (**C**) neonates are shown. H/K-ATPase immunostaining reveals that a defined parietal cell-depleted region representing the antrum is absent with loss of *Barx1* regardless of whether Bapx1 is functional or not. Other markers such as Cdx2 and Alcian blue staining gave similar results (data not shown). **(D–G)** *In situ* mRNA analysis confirms the overlapping schema depicted in panel **A** and reveals an expression hierarchy between *Barx1* and *Bapx1*. *Barx1* mRNA, which is expressed throughout fetal stomach mesenchyme, is unaltered in level or distribution with loss of *Bapx1* (**D–E**), whereas *Bapx1* expression in the embryonic hindstomach is severely compromised with *Barx1* loss

(**F,G**; arrows and dashed outlines mark hindstomach mesenchyme). *Bapx1* expression was also observed in wild-type spleen (**F**, arrowhead and dashed outline), but loss of this signal occurred selectively in hindstomach; somites, another prominent site of *Bapx1* expression (**G** inset, small arrows), were unaffected. **(H,I)** Confirmation of loss of *Bapx1* expression by qRT-PCR and immunoblotting. RNA was isolated from stomachs dissected at multiple developmental stages and normalized to *Gapdh* levels (**H**) or Bapx1 protein levels were examined in E13.5 stomachs by immunoblot analysis (**I**). Bapx1 expression was virtually undetectable by either method in *Barx1*$^{-/-}$ stomachs.