

Clustered arrangement of winged helix genes *fkh-6* and *MFH-1*: possible implications for mesoderm development

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SUMMARY

The 'winged helix' or 'forkhead' transcription factor gene family is defined by a common 100 amino acid DNA binding domain which is a variant of the helix-turn-helix motif. Here we describe the structure and expression of the mouse *fkh-6* and *MFH-1* genes. Both genes are expressed in embryonic mesoderm from the headfold stage onward. Transcripts for both genes are localised mainly to mesenchymal tissues, *fkh-6* mRNA is enriched in the mesenchyme of the gut, lung, tongue and head, whereas *MFH-1* is expressed in somitic mesoderm, in the endocardium and blood vessels as well as the condensing mesenchyme of the bones and kidney and in head mesenchyme. Both genes are located within a 10 kb region on mouse chromosome 8

at 5.26±2.56 cM telomeric to *Actsk1*. The close physical linkage of these two winged helix genes is conserved in man, where the two genes map to chromosome 16q22-24. This tandem arrangement suggests the common use of regulatory mechanisms. The *fkh-6/MFH-1* locus maps close to the mouse mutation *amputated*, which is characterised by abnormal development of somitic and facial mesoderm. Based on the expression patterns we suggest that a mutation in *MFH-1*, not *fkh-6* is the possible cause for the *amputated* phenotype.

Key words: transcription factor, winged helix, intestinal mesenchyme, somitic mesoderm, *amputated*, mouse, *fkh-6*, *MFH-1*

INTRODUCTION

The 100 amino acid 'forkhead' DNA binding domain defines a large and growing gene family with more than 80 members in species ranging from yeast to man (reviewed by Lai et al., 1993). The determination of the crystal structure of the DNA-binding domain of HNF-3 γ revealed that DNA recognition is mediated by a variant of the helix-turn-helix motif (termed 'winged helix') which contains two loops or 'wings' at the C-terminal side of the helix-turn-helix (Clark et al., 1993). The winged helix proteins bind DNA as monomers and make base-specific contacts by the α helix H3 and loop W2 which bind in the major groove of DNA. A 20 amino acid region N-terminal to helix 3 also has been shown to be important in the determination of binding site specificity (Overdier et al., 1994). Analyses of expression patterns as well as gain- or loss-of-function mutations have implicated the winged helix genes in pattern formation during embryogenesis. The *Hnf-3 β* gene product, for example, is normally found in the node, notochord, endoderm and central nervous system during early stages of mouse development (Ang et al., 1993; Monaghan et al., 1993; Sasaki and Hogan, 1993). Ectopic expression of HNF-3 β in the midbrain and hindbrain of transgenic mice leads to changes in the expression of floorplate-specific genes and to abnormal neural patterning (Sasaki and Hogan, 1994). Loss of function of the mouse *Hnf-3 β* gene through targeted mutagenesis results in severe defects in midline

development, specifically the absence of the notochord and floorplate (Ang and Rossant, 1994; Weinstein et al., 1994).

Several other members of the winged helix gene family have been implicated by their expression patterns to play a role in defining mesoderm. Among these are mesoderm/mesenchyme fork head 1 (MF-1, Sasaki and Hogan, 1993; also termed *fkh-1*, Kaestner et al., 1993), MF-2 (Sasaki and Hogan, 1993) and *MFH-1* (Miura et al., 1993). MF-1 expression was detected in headfold mouse embryos in paraxial mesoderm and later in the mesenchyme of the first branchial arch and declines after day 9.5 p.c. (Sasaki and Hogan, 1993). *MFH-1* gene expression was detected from day 9.5 onward in somites and subsequently in cartilaginous tissues and the metanephros (Miura et al., 1993).

We have previously isolated 16 members of the winged helix family from mice (*Hnf-3 α , β and γ* , Kaestner et al., 1994; and *fkh-1* to *fkh-6*, Kaestner et al., 1993, 1995, 1996; Tanoue, Kaestner and Schütz, unpublished data), which exhibit specific and diverse patterns of expression in adult tissues. Here we report the detailed characterisation of *fkh-6*, which was found to be closely linked to *MFH-1* and which together with *MFH-1* defines domains of non-notochordal mesoderm.

MATERIALS AND METHODS

Library construction and cDNA and genomic cloning

An oligo(dT)-primed cDNA library from mouse day 8.5 p.c. (post

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1   AGATTTTCAGCAATGAAATTTTAAATTAATGTGGTGGGGTGGAGAACACAAGGACTGTTTATCATAGACAATTTATTTTCCAGCGCTAAGTCAACACATAA   100
101 TAGCAAACCTTACAACAATTATTTAACATTTTTAAAGCCATGAAGAAGGGACAAGCGCGCAGCGGCTGGGGAGAGCGGCTGATCGCAGGGCAGTCGCACA   200
201 GAGGGCTCCCCAGGAGGGCCCTGGTGCGGGGCAAAGTCTTAGGACTCCCCGGTGGAGCGGAGAGGCTGTCTGCACCTCTTTCAGTCCCCC      300
                                     M S H L F S P P      8

301 GCTGGCCGCTCTGGCAGCCTCGCCGCTGTTGTACGTGTACAGCCCCGAGAGGCGCTGGGCTGCCCTTGGCCTTCGCCCTGCGGCTGCACTGGCCGGCCCG   400
   L A A L A A S P L L Y V Y S P E R P G L P L A F A P A A A L A G P   41

401 GGCCGCTCGAGCCCCGAGAAGCCGCCCTACAGCTACATCGCTCTTATAGCCATGGCGATCCAGGATGCTCCCGAGCAGAGGGTCACACTGAACGGCA   500
   G R V E P P Q K P P Y S Y I A L I A M A I Q D A P E Q R V T L N G I   75

501 TCTACCAGTTCATCATGGATCGCTTCCCGTTCACCACGACAACCGCAAGGCTGGCAGAACAGCATCCGCCACAACCTGTCTGCTCAACGAGTGTCTCGT   600
   Y Q F I M D R F P F Y H D N R O G W Q N S I R H N L S L N E C F V   108

601 GAAGTGGCCACGTGAGAAGGGCGCGCCGGCAAGGGCAGCTACTGGACCCCTGGACCCCGCTGTGGACATGTTTGAACGGCAATTATCGGCGCAGG   700
   K V P R E K G R P G K G S Y W T L D P R C L D M F E N G N Y R R R   141

701 AAGAGGAAGCCAAGCCCGCGGGTTCGCCGAGGCCAAGCGCACCCGGGTCGAGCCCGGAGTCCGAGGTGGGCTGCGATGTAGGGTCCCCGGACC   800
   K R K P K P A A G S P E A K R T R V E P P E S E V G C D V G S P D L   175

801 TGTTGGCCACTGCACTCCCGACGCGCGCGCGGATCGCTCCCAATCCCCGGCAGTAGGCACCGCGCGCCCGGCTCCCTCCCTGGCCCGGCCCTGAGCC   900
   V A T A L P T R A P D R S Q S P A V G T A R P A L L P W P G P E P   208

901 CCGGACCCCGACGCGGACCTCACAGTCCAGGGCGCAGGGGCGAGTGGCAAGCGGCCAGCTCCAGCGGTCGGCACACCACCTGGGGTCCCCATATATACC   1000
   R D P D A D L T V Q G A G A V A S G Q L Q R S G T P P G V P Y I P   241

1001 CACCCCGAGCGGCTCCCAAAAGGTTCCAAGTCAAGAGTTTTCAGCATCGACAGCATTGTTGGCCGAGACCGACCCAGCCCTCAGGGGCCAAGCACCGG   1100
   H P Q R L P K R F Q V K E F Q H R Q H F G R R P T P A S G A E A P G   275

1101 GGATCCCTAAGCCGCTGCTGGCGCGTGGGCTCCTCTCTGTGGCTGCCTCCTCCGCGCTAGCGCTCCCTTCAACGCTTCGCTGGTCTTCGACGCGCA   1200
   I P K P V P G A L G S S L L A A S S G L A P P F N A S L V F D A H   308

1201 CGTCCAGGGCGGCTTTTCCAGCTGGGGATCCCTTCTCTTCTTATTTTCTCTCTGAGGTTCCCGAGGCCACAGTGTCTCGTTTCCACTAAGCGGATTA   1300
   V Q G G F S Q L G I P F L S Y F P L Q V P E A T V L R F H *   337

1301 GCGGCTGCTTCCCTGCTCGCGATCCCCCACCTCCAGTGGCAATGCTGTGGGCGAAGGAGTCGCCCCGGTCTCTGCCCTGGCAGAGACTGAGGGTT   1400
1401 TGGAGCAGCGTACCCGTGCGCGCCAAAGTCTGCACTGAGGGGCTCGTCCATCTGCTTTCTCCGAGATGACTTAACCAGCCACCGGAAGCTTGCAGA   1500
1501 TTTAAAGACTGGTCCAGTAGAGACATGGACGCGCACACTCAGCCCTCAGGTTCTGCTTCCAGCAGAAGCCCTCGTAGGCTTTGGCGGCTGTGACA   1600
1601 GTGACCACCACAAGTCCCCACTCGGACCTGAGTCTCTGCTGACCTGAGGCGAGGACTTAGAGATAAGCGAACAGCTTATGTGGAGTTCAACTGGA   1700
1701 TCATGGAAGGCCTCAGCGGGCTCCGTGTGGCATAGGCCTTGGCTTTGATCTCATTGGATGT   1761
    
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Fig. 1. Nucleotide and translated amino acid sequence of the mouse *fkh-6* gene. The sequence of the gene and the corresponding amino acid sequence of the longest open reading frame is shown. The sequence of the 100 amino acid *forkhead* DNA binding domain is underlined. These sequences have been deposited in the EMBL data base under the accession numbers X92498 and X92499.

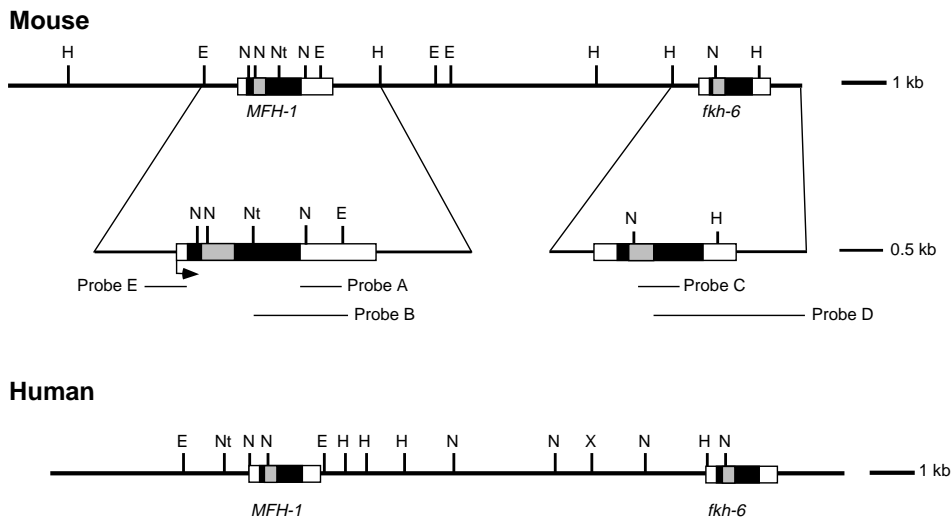


Fig. 2. Physical map of the mouse and human *fkh-6*/*MFH-1* loci. The restriction maps of the genes are shown together with the extent of the lambda phage clones from which they were derived. The exons are shown as large boxes, the translated regions as black and the winged helix domains as stippled boxes. The probes labelled A-E are referred to in the text. E, *EcoRI*; Nt, *NotI*; N, *NcoI*; X, *XbaI*, H, *HindIII*.

coitum) embryos (Kaestner et al., 1995) was screened with probes B and D (see Fig. 2) derived from the *MFH-1* and *fkh-6* containing genomic clone described previously (Kaestner et al., 1993) using high stringency hybridisation and washing conditions (Church and Gilbert, 1984). Five hybridising lambda phages corresponding to *MFH-1* were purified and the cDNAs subcloned into Bluescript (Stratagene) and

sequenced (Sanger et al., 1977) on both strands. A human placenta genomic library (Stratagene) was screened using probe C (see Fig. 2) to obtain the human *MFH-1/fkh-6* locus. Fragments of the genomic phage clone hybridising to *fkh-6* and *MFH-1* specific probes were subcloned and partially sequenced to confirm the identity of the human *fkh-6* and *MFH-1* genes.

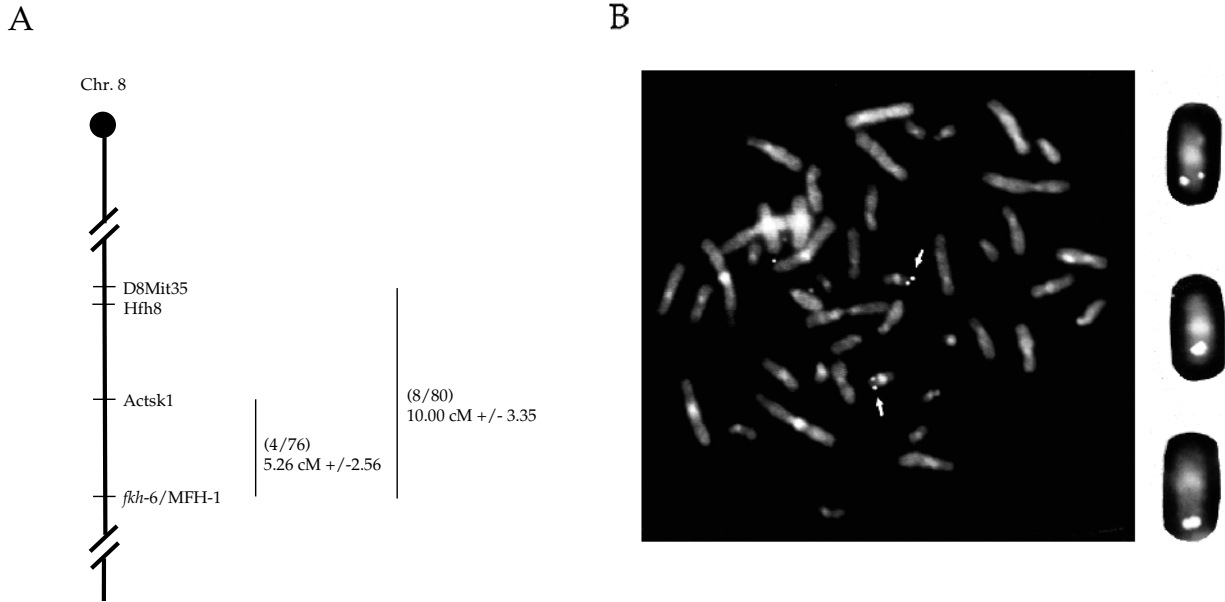


Fig. 3. Chromosomal localisation of the mouse and human *fkh-6*/MFH-1 loci. (A) The murine *fkh-6*/MFH-1 locus was mapped to chromosome 8 by linkage analysis as described in Materials and Methods. The numbers refer to the recombinants observed between the *fkh-6*/MFH-1 probe and D8Mit35 and Actsk1, as well as the distance in centimorgans (cM) \pm the standard error. (B) As revealed by fluorescence in situ hybridisation, the human *fkh-6*/MFH-1 locus maps to chromosome 16q22-24. Detection of the hybridised probe via rhodamine revealed highly specific signals as indicated by the arrows in the large panel showing a complete metaphase spread. Panels on the right present additional chromosome 16 homologues from other metaphase spreads to illustrate the subchromosomal localisation on chromosome 16q22-24.

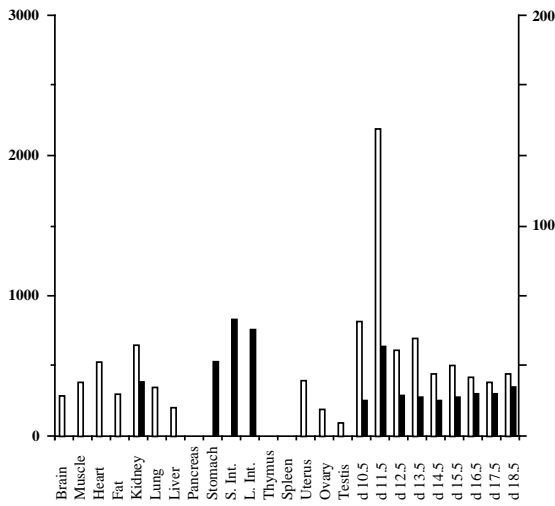


Fig. 4. Expression of the *fkh-6* and MFH-1 mRNAs during mouse embryogenesis and in adult mouse tissues. 40 μ g of total RNA from the adult tissues or whole embryos of the developmental stages indicated were analysed by RNase protection as described in Materials and Methods. The signals obtained were quantified using a phosphoimager and corrected for the specific activity of the probes used and reflect the true molar ratios of the two mRNAs. Note the different scales for the two mRNAs: open bars, MFH-1 mRNA, scale bar on the left; black bars, *fkh-6* mRNA, scale bar on the right.

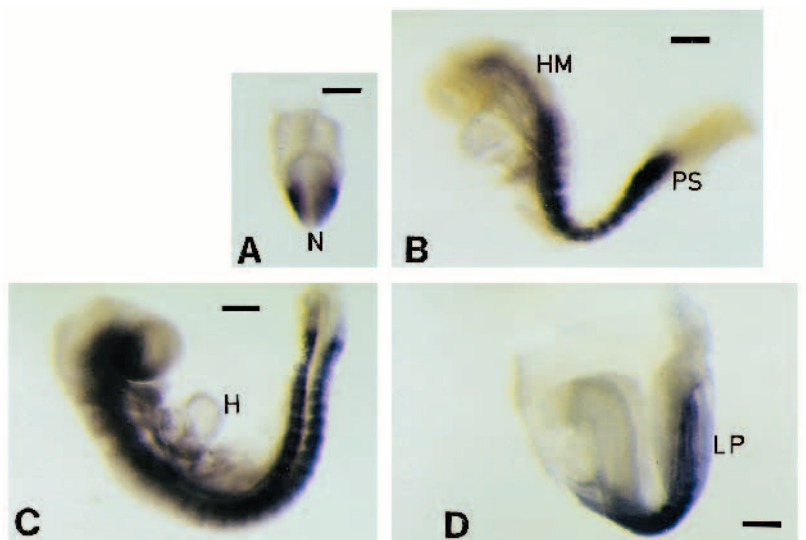


Fig. 5. Expression of the *fkh-6* and MFH-1 genes in day 7.5 (A) and 8 p.c. (B-D) mouse embryos. Whole-mount in situ hybridisation with antisense probes specific for MFH-1 (A-C) and *fkh-6* (D) was performed as described in Materials and Methods. MFH-1 is expressed in mesoderm anterior and posterior of the node in late streak embryos (A), and subsequently in presomitic, somitic and head mesoderm (B,C). Transcripts produced by the *fkh-6* gene are detected in day 8.5 embryos in posterior mesoderm (D). Scale bars represent 50 μ m in A and 100 μ m in B-D. N, node; HM, head mesoderm; H, heart; LP, lateral plate mesoderm, PS, presomitic mesoderm.

RNA isolation and RNase protection analysis

Total RNA from a variety of mouse tissues or whole mouse embryos was isolated after homogenisation in guanidinium thiocyanate (Chomczynski and Sacchi, 1987). The quality of the RNA preparations was controlled by ethidium bromide staining of the 18S and 28S rRNAs after electrophoretic separation of the RNA in denaturing agarose gels. RNase protection analysis was performed as described previously (Kaestner et al., 1989) using [α - 32 P]UTP-labelled antisense RNA probes derived from Bluescript (Stratagene) subclones containing a 556 bp *NcoI/BamHI* fragment of the *fkh-6* gene and a 447 bp *NcoI/EcoRI* fragment of the *MFH-1* gene (probes A and C in Fig. 2). A 337 bp subclone of the mouse TBP (TATA-box binding protein) gene (Tamura et al., 1991) was used as an internal control, as the mRNA of this gene is expressed in all tissues at roughly equal levels, with the exception of ovary and testis. The antisense probes were hybridised overnight against 40 μ g of total RNA at 54°C in 80% formamide. Excess probes were removed by digestion with RNases A and T1 and the protected probe fragments analysed on denaturing 6% polyacrylamide gels. The signals obtained were quantified on a Molecular Dynamics phosphorimager and normalised for the number of UMP residues incorporated in the hybridising portion of each probe and represent the molar ratios of the two mRNAs.

In situ hybridisation

Mouse embryos and fetuses were obtained from matings between NMRI mice. By convention the day of the appearance of the vaginal plug was counted as day 0.5. Embryos were fixed in 4% paraformaldehyde (pH 7.2) overnight, dehydrated through an ethanol series, cleared in toluene and embedded in paraffin. 6 μ m sections were cut for each stage. In situ prehybridisations and hybridisations using probes B and D (see Fig. 2) as well as sense controls were carried out as described by Wilkinson (1992). Slides were dipped in Kodak NTB2 emulsion diluted 1:1 with water and exposed at 4°C for 7 to 14 days and developed using Kodak D19 developing solution and Kodafix at 15°C for 4 minutes. Sections were stained using eosin and hematoxylin and visualised using a Zeiss Axiophot microscope. Whole-mount in situ hybridisations using digoxigenin-labelled antisense RNA probes B and D (see Fig. 2) were performed as described previously (Conlon and Hermann, 1993).

Chromosomal localisation

Human metaphase spreads were prepared from peripheral blood lymphocytes following cell stimulation, mitotic arrest, hypotonic treatment and methanol/acetic acid fixation. Lambda phage C4 DNA containing both the human *MFH-1* and *fkh-6* genes was labelled by nick-translation using digoxigenin-labelled nucleotides, and in situ hybridisation was carried out as described elsewhere (Lichter et al., 1990). The hybridised probe was detected via rhodamine and chromosomes were banded by DAPI staining (4',6'-diamidino-2-phenylindole).

Linkage analysis was carried out using the DNA samples of the European Backcross (EUCIB) kindly provided by the European Backcross Collaborative Group (The European Backcross Collaborative Group, 1994). A 570 bp fragment of the mouse *fkh-6* gene was amplified with primers A (CCATGGACCTCTGGACTATC-TAGTTG) and B (CTTGGTCCCTCCTCTTCACACCC) in a PCR buffer containing 1.5 mM MgCl₂ with 35 cycles of 94°C (30 seconds), 66°C (60 seconds) and 72°C (120 seconds). The PCR products were digested with HpaII and analysed on a 1.5% agarose gel after staining of the DNA with ethidium bromide. The *Mus musculus* allele produces bands of 260, 205, 66 and 55 bp, while the *Mus spretus* allele results in two bands of 316 and 255 bp.

RESULTS

Characterisation of the *fkh-6* and *MFH-1* genes

In order to understand the relationship of *fkh-6* to the other

winged helix genes, we determined the primary sequence of the *fkh-6* coding region. Although we were not able to obtain full length cDNAs from library screens, we have ascertained that the *fkh-6* gene is transcribed and contains only one exon (Figs 3, 4, 5 and data not shown). The *fkh-6* mRNA encodes a protein of 337 amino acids with a calculated relative molecular mass of 35870, which is in good agreement with the size of the in vitro transcribed and translated protein (data not shown). The complete sequence is depicted in Fig. 1. The presumed winged helix DNA binding domain is underlined. No striking homology to the transcriptional activation domains identified in HNF-3 β (Pani et al., 1992) are present in this sequence, but a large proportion of proline residues (14.8%) was found. A similar proline-rich region was shown to function as transactivation domain in the winged helix protein 'myocyte nuclear factor' (Bassel-Duby et al., 1994). The winged helix domain of *fkh-6* is most closely related to those of the mouse genes *fkh-1* and *MFH-1* (77% identity with both genes at the amino acid level; Kaestner et al., 1993; Miura et al., 1993). Outside the DNA binding domain no significant homologies with winged helix or other genes were found in the databases.

During the analysis of the mouse *fkh-6* gene we discovered a second winged helix domain located on the same genomic λ phage clone. Sequence analysis revealed that this second winged helix domain corresponds to the previously described *MFH-1* cDNA (Miura et al., 1993). Several *MFH-1* cDNAs were isolated from a day 8.5 p.c. mouse embryo library which extend 3' to include a consensus polyadenylation signal and poly(A) tail. The start site of transcription was determined by RNase protection assay (data not shown) using probe E (Fig. 2A) derived from the genomic *MFH-1* locus. The complete cDNA sequence for the mouse *MFH-1* gene encompasses 2340 nt, which together with a poly(A) tail is in good agreement with the size (2.5 kb) of the message estimated from northern blot analysis (data not shown). Sequencing revealed an additional guanidine nucleotide at position 49 of the previously published *MFH-1* sequence which leads to a new initiator ATG further upstream. The *MFH-1* cDNA thus encodes a protein of 495 instead of 462 amino acids and a calculated relative molecular mass of 53081, which agrees with the size of the in vitro translated *MFH-1* protein of 53×10^3 (Miura et al., 1993 and data not shown). The updated *MFH-1* sequence has been deposited in the EMBL data base. The precise arrangement of the two genes is detailed in Fig. 2. The *MFH-1* gene lies approximately 8 kb 5' to *fkh-6* and both genes are transcribed in the same direction. Each gene is encoded by only one exon. A similar tandem arrangement has been described for the human winged helix genes *HBF-1* and *HBF-2*, which are both expressed in the brain and which are localised on human chromosome 14 (Wiese et al., 1995) while the other rodent winged helix genes have been found in multiple chromosomal locations (Avraham et al., 1992, 1995; Kaestner et al., 1995). To investigate whether the close linkage of the *fkh-6* and *MFH-1* genes is unique to mice, we attempted to clone the orthologous locus from a human genomic library and characterised it through hybridisation and sequence analysis. The regions of the human *fkh-6* and *MFH-1* genes sequenced show 85 and 94% identity at the nucleotide level, respectively, to the corresponding mouse genes. As is shown in Fig. 2, the human *fkh-6* and *MFH-1* genes are

arranged in a remarkably similar pattern to the mouse genes, which taken together with the sequence similarity suggests that these loci are orthologous.

The mouse *fkh-6/MFH-1* locus was mapped by linkage analysis using the DNA collection of the European backcross (The European Backcross Collaborative Group, 1994; see Materials and Methods). Analysis of DNAs from 100 random recombinants assigned *fkh-6/MFH-1* to chromosome 8 (LOD score of 16), 5.26±2.56 cM telomeric to *Actsk1* (Fig. 3A). Only one other winged helix gene, termed *Hfh-8*, has been mapped to chromosome 8, but closer to the centromer in the vicinity of *Aprt* (Avraham et al., 1995). This gene, which is involved in the regulation of surfactant protein gene expression in the lung (Clevidence et al., 1994), is only distantly related to *fkh-6* and *MFH-1* (44 and 47% identity at the nucleotide level). Interestingly, the mouse autosomal recessive mutation *amputated* has been mapped to the telomeric region of chromosome 8 (Lyon and Searle, 1989). Mice homozygous for this mutation exhibit defects in somitic and facial mesoderm and limb formation (Flint and Ede, 1978, 1982). Although this mutation has not been mapped relative to the markers used in this study, the expression pattern of *MFH-1* and the phenotypic consequences of the *amputated* mutation make *MFH-1* a candidate gene for this mutation. The human *fkh-6/MFH-1* locus was mapped by fluorescence in situ hybridisation of the entire phage DNA against metaphase chromosome spreads. Hybridisation signals were found only at one chromosomal locus (Fig. 3B) and no other fluorescence spots were observed in any other chromosomal region. In 34 analysed metaphase spreads, 71% of the target sequences were specifically labelled. As revealed by DAPI banding, the human *fkh-6/MFH-1* locus maps to chromosome 16q22-24 (Fig. 3B), extending the syntenic relationship between mouse chromosome 8 and human chromosome 16. No human hereditary condition that could be immediately related to *fkh-6/MFH-1* function has yet been mapped to this position.

Expression analysis of the *fkh-6* and *MFH-1* genes

In order to gain insight into the potential function of the *fkh-6* and *MFH-1* genes and to assess whether their close linkage results in common usage of regulatory elements governing their expression, we analysed the transcript distribution in adult mice and whole embryos. RNAs from fifteen adult mouse tissues were analysed for expression by RNase protection with probes A and C outlined in Fig. 2. The *fkh-6* mRNA is expressed in stomach, intestine and weakly in kidney (Fig. 4). *MFH-1* expression is strongest in adult kidney in concordance with the findings of Miura et al. (1993), but is also detectable at lower levels in brain, heart, muscle, uterus, lung, liver, ovary and testis. During embryonic development, both mRNAs are present from day 10.5 onward with decreasing expression after day 11.5 (Fig. 4). The expression of *MFH-1* in whole embryos is always 20- to 40-fold stronger than that of *fkh-6* (Fig. 4).

In order to precisely define the cellular localisation of the *fkh-6* and *MFH-1* mRNA in midgestation embryos, in situ hybridisation studies were performed on embryos starting at day 7.5 p.c. of gestation with antisense probes (labelled B and D in Fig. 2). Transcription of the *fkh-6* gene is activated in embryos of day 8 p.c. and is found in posterior mesoderm by whole-mount in situ hybridisation (Fig. 5D). Additional expression domains were characterised by in situ hybridisation of sectioned embryos. Transcripts were not detectable in early

headfold embryos (Fig. 6A), but appear on day 9.5 of gestation in the mesenchyme surrounding the anterior gut and lung as well as mesenchyme of the palate (Fig. 6G). This expression is maintained until day 12.5 p.c. (see below).

Whole-mount in situ hybridisation demonstrates that the *MFH-1* gene is activated prior to *fkh-6* in late primitive streak stage embryos in the mesoderm both anterior and posterior to the node, but not in the node itself (Fig. 5A). The signal extends to the primitive streak but is excluded from the allantois and extraembryonic regions. In day 8 p.c. embryos, just prior to turning, expression is weak in the head mesenchyme and becomes stronger in somitic and presomitic mesoderm (Fig. 5B). After turning, expression is maintained in the somites and increases in head mesenchyme (Fig. 5C). In situ hybridisation of sectioned embryos demonstrates that *MFH-1* expression is absent from day 6.5 embryos (data not shown), but is present in the mesoderm of late primitive streak and headfold stages (Fig. 6C,D). No transcripts are detectable in the endoderm, surface ectoderm or in the extraembryonic regions of the embryo. In 8 to 8.5 day old embryos, *MFH-1* mRNA is localised to all mesenchymal lineages but subsequently becomes localised to the somites, presomitic mesoderm, head and endocardial mesoderm (Fig. 6E). At later stages, *MFH-1* transcription is maintained in the mesenchyme from head to tail, including the dorsal aorta (Fig. 6H) and the somitic mesoderm, where it becomes localised to the sclerotome (Fig. 6H and data not shown), but is excluded from gut mesenchyme.

In order to allow the assessment of potential overlap in the expression of the two genes, we performed in situ hybridisation studies on adjacent sections of day 12.5 p.c. mouse embryos with antisense probes for *MFH-1* and *fkh-6*. As is demonstrated in Fig. 7, transcripts for both genes are found in partially overlapping regions of the head mesenchyme, for instance in the precartilaginous primordia of the temporal bones, the nasal, otic and optic capsule, the nasal septum and the tongue (Fig. 7A,B,E,F). Transcripts of the *MFH-1* gene are, however, more abundant than those of *fkh-6* and are additionally localised to the mesenchyme surrounding the trachea and the cartilage primordia surrounding the neural tube (Fig. 7F), while *fkh-6* mRNA is exclusive to the teeth. In the trunk, *fkh-6* transcripts are found in the mesenchyme surrounding the notochord, the mesenchyme of the lung and developing kidney, the wall of the intestine and stomach and at a low level in the condensing cartilage of the bones (Fig. 7C,D). The *MFH-1* gene is transcribed in the condensing cartilage of the tail and limb bones, the blood vessels and the urogenital system (Fig. 7G,H).

In summary, there are overlapping expression domains of the two genes of the *fkh-6/MFH-1* locus in the mesenchyme of the head, bones and urogenital system, but there are also areas of mutual exclusion. For example, *MFH-1* is a marker for developing blood vessels, while *fkh-6* is specific for the mesodermal components of the gut.

DISCUSSION

Is the *fkh-6/MFH-1* locus orthologous to *sloppy* paired of *Drosophila*?

Characterisation of cDNA and genomic clones of the mouse

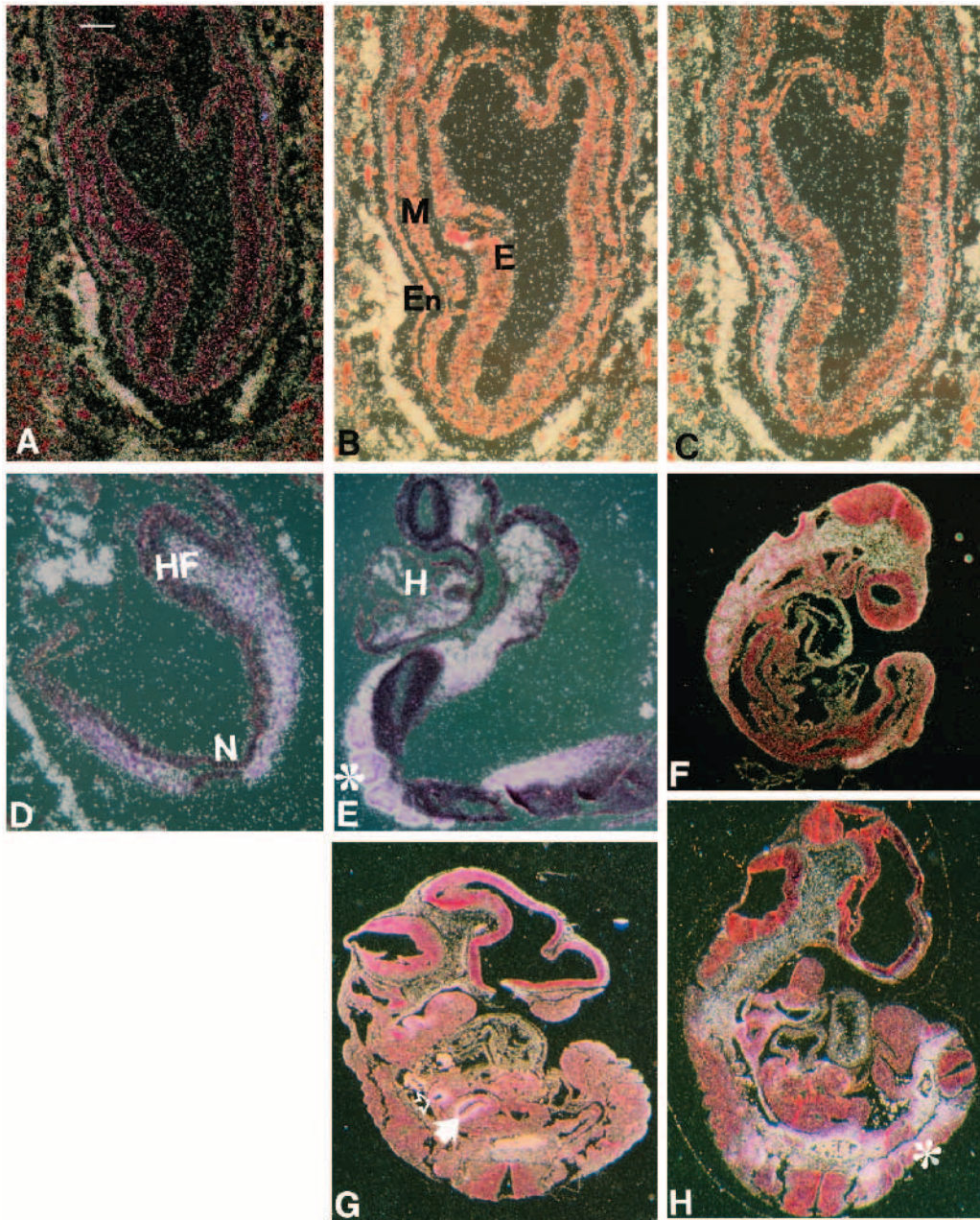


Fig. 6. Expression of the *MFH-1* and *fkh-6* genes in mouse embryos from day 7.5 to 10.5 p.c. (A-D) Sagittal sections of day 7.5 p.c. mouse embryos. No hybridisation to the *fkh-6* antisense probe (A) and the *MFH-1* sense probe (B) is detected. (C-D) Sagittal sections of day 7.5 p.c. embryos labelled with the *MFH-1* antisense probe detects mRNA in the embryonic mesoderm of headfold stage embryos both anterior and posterior to the node, but excluded from the extraembryonic mesoderm. (E) Sagittal section of an unturned day 8.25 mouse embryo. *MFH-1* transcripts are detected in the somites (asterisk), the mesoderm of the head and the endocardium. (F) Sagittal section of a day 8.75 p.c. embryo indicates continued expression of *MFH-1* in the mesoderm of the head and somites. (G) Sagittal section of a day 9.5 p.c. embryo labelled with the *fkh-6* antisense probe stains the mesenchyme of the lung bud (open arrow) and midgut (filled arrow). (H) Sagittal section of a day 10.5 p.c. embryo shows expression of the *MFH-1* gene in the somites (asterisk). The dorsal aorta is also labelled. M, mesoderm; E, ectoderm; EN, endoderm; H, heart; HF, headfold. Scale bar represents 100 μ m in A-D and 200 μ m in E-H.

fkh-6 and *MFH-1* genes have localised these genes in a close tandem array, which suggests common regulatory mechanisms or functional redundancy. A similar clustering has been described for the winged helix genes *sloppy paired* 1 and 2 of *Drosophila* (*slp1* and *slp2*; Grossniklaus et al., 1992). Mutation of the *sloppy paired* locus leads to a phenotype reminiscent of the pair-rule class of segmentation genes with impaired involution of the head and partial deletion of naked cuticle in the odd-numbered abdominal segments and the mesothorax. The expression pattern of the two genes is complex but very similar, with the activation of *slp1* preceding that of *slp2*. The functional importance of the individual *sloppy paired* genes was explored by Cadigan et al. (1994) who analysed the phenotypes of embryos containing varying combinations of functional *slp* genes or ubiquitously overexpressed *slp1* or *slp2*. In these studies it was demonstrated that until gastrulation only

slp1 is required, while at later stages the two genes are redundant in many respects. Based on these observations the authors concluded that the two *slp* proteins are biochemically equivalent and that the greater requirement for *slp1* is explained in large part by its earlier expression (Cadigan et al., 1994).

Could a similar relationship exist between *MFH-1* and *fkh-6*? The *MFH-1/fkh-6* locus does not appear to be orthologous to the *sloppy paired* locus despite the similar structure of the loci. The sequence similarities between the *Drosophila* and mouse genes are limited (only 62 or 58% identical amino acids in the winged helix domain between *MFH-1* and *slp1* and *slp2*, respectively, versus 72% amino acid identity between *MFH-1* and *Drosophila forkhead*; Weigel et al., 1989) and the characteristic carboxy-terminal sequence of the *slp* genes is not present in *MFH-1* or *fkh-6*. In addition, the expression domains

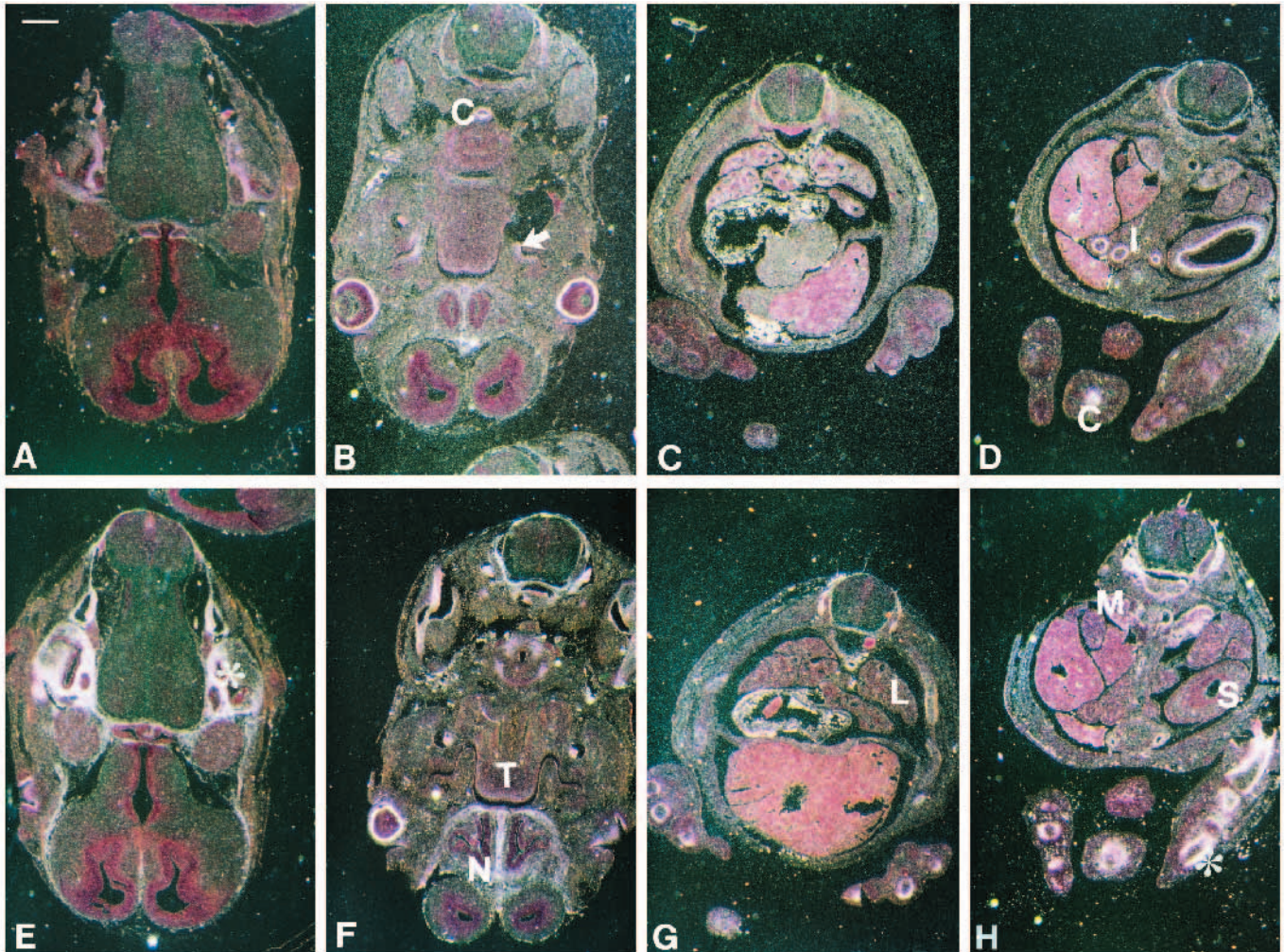


Fig. 7. Expression of the *MFH-1* and *fkh-6* genes in mouse embryos on day 12.5 p.c. Transverse sections at various levels were hybridized with antisense probes to *fkh-6* (A-D) or *MFH-1* (E-H) (A,E) Sections on the level of the otic capsule indicate strong expression of the *MFH-1* gene in the precartilaginous primordium throughout the head, with much weaker, but overlapping expression of *fkh-6*. (B,F) Sections through the head at the level of the eyes show transcripts for *fkh-6* surrounding the notochord (labelled C), the developing cartilage of the nose and tongue and the developing teeth (arrow), while those of *MFH-1* are excluded from the notochord, but are present in the precartilaginous primordia of the nasal, otic and optic capsules and the nasal septum (N) as well as the tongue (T). *MFH-1* signal is also seen in the mesenchyme surrounding the trachea and neural tube. (C,G) Sections through the thorax demonstrate *fkh-6* expression in the lung mesenchyme and the oesophagus, while *MFH-1* expression is localised to the limb cartilage. (D,H) Transverse sections through the abdomen show *fkh-6* and *MFH-1* mRNAs in the urogenital system and limb (asterisk) and tail cartilage, and *fkh-6* mRNA additionally in the intestinal and stomach mesenchyme as well as around the notochord. The scale bar represents 200 μ m. Abbreviations: C, notochord; I, intestine; L, lung; M, metanephros; N, nose; S, stomach; T, tongue.

are dissimilar. Furthermore, in contrast to the *slp* genes, the two mouse genes have only partially overlapping expression patterns and are probably not redundant (see below).

The *fkh-6* and *MFH-1* genes define overlapping mesodermal domains

The *fkh-6/MFH-1* locus contains two genes which are expressed in partially overlapping domains. Transcripts for both genes are found in the mesenchyme of the developing head, kidney and bones. The *fkh-6* gene is active in addition in the mesenchymal layer of the gut, but is excluded from the gut epithelium, which is derived from the definite endoderm. Proper differentiation of the intestinal epithelium is thought to depend on the establishment of functional interactions with the adjacent mesenchyme (Birchmeier and Birchmeier, 1993). A

possible role of the *fkh-6* gene could lie in the establishment or maintenance of such interactions, or more specifically, in the establishment of an inductive signal from the gut mesenchyme to the epithelium. Preliminary results from our analysis of mice homozygous for a targeted mutation in the *fkh-6* gene suggest that this interaction has been impaired. Mice lacking this gene exhibit abnormal development of the stomach and small intestine, both areas with relatively high and exclusive *fkh-6* expression (Kaestner and Schütz, unpublished data).

The *MFH-1* gene, in addition to its expression domain in the head mesenchyme, seems to play a role in somite formation, as it is expressed in paraxial mesoderm from its inception, and later on in pre-somitic as well as somitic mesoderm, where transcripts become localised to the sclerotomes. In addition,

MFH-1 transcripts are also localised to the developing heart and blood vessels as well as the kidney and mesenchyme of the limbs, the latter expression domains were also described by Miura et al. (1993).

The regulation of the *fkh-6/MFH-1* locus must necessarily be complex to accommodate the similar yet divergent expression patterns of the two genes. It seems plausible that a common enhancer element could govern the expression of the two genes in the head mesenchyme, but that additional regulatory elements may be required for the individual expression domains of the two genes.

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