Imprinting of IGF2 P0 transcript and novel alternatively spliced INS-IGF2 isoforms show differences between mouse and human


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Genomic imprinting is limited to a subset of genes that play critical roles in fetal growth, development and behaviour. One of the most studied imprinted genes encodes insulin-like growth factor 2, and aberrant imprinting and DNA methylation of this gene is associated with the growth disorders Beckwith–Wiedemann and Silver–Russell syndromes and many human cancers. Specific isoforms of this gene have been shown to be essential for normal placental function, as mice carrying paternal null alleles for the Igf2-P0 transcript are growth restricted at birth. We report here the identification of three novel human transcripts from the IGF2 locus. One is equivalent to the mouse Igf2-P0 transcript, whereas the two others (INSIGF long and short) originate from the upstream INS gene that alternatively splices to downstream IGF2 exons. In order to elucidate the molecular mechanisms involved in the complex imprinting of these novel IGF2 transcripts, both the allele-specific expression and methylation for all the IGF2 promoters including P0 and the INSIGF transcripts were analysed in human tissues. Similar to the mouse, the human IGF2-P0 transcript is paternally expressed; however, its expression is not limited to placenta. This expression correlates with tissue-specific promoter methylation on the maternal allele. The two novel INSIGF transcripts reported here use the INS promoter and show highly restricted tissue expression profiles including the pancreas. As previously reported for INS in the yolk sac, we demonstrate complex, tissue-specific imprinting of these transcripts. The finding of additional transcripts within this locus will have important implications for IGF2 regulation in both cancer and metabolism.

INTRODUCTION

Genomic imprinting is an epigenetic phenomenon that results in the expression of only one allele in a parent-of-origin-dependent manner (1). To date, more than 70 imprinted genes have been described in the mouse (http://www.mgu.har.mrc.ac.uk/imprinting/imprinting.html). One of the first imprinted genes to be described was the paternally expressed insulin-like growth factor 2 (Igf2) (2). Over the past decade, this gene has been extensively studied because it is a potent embryonic growth factor that is crucial during embryogenesis and is implicated in the human disorders Beckwith–Wiedemann syndrome (BWS) (MIM 130650), Silver–Russell syndrome (SRS) (MIM 180860) and in tumourigenesis (3–5). The Igf2 gene, comprising many alternatively spliced transcripts from different promoters, maps to a large imprinted domain on distal mouse chromosome (Chr) 7 and is flanked 5′ by insulin (Ins2) and 3′ by the non-coding

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transcript, a region of conserved synteny with human Chr 11p15 (Fig. 1). In both human and mouse, the paternal expression of \( \text{Ig} \text{f2} \) and \( \text{In} \text{s2} \) is closely linked to the expression of the reciprocally imprinted \( \text{H}1\text{9} \) transcript (6). Research into the imprinting control of this domain has revealed a complicated regulatory mechanism that utilizes multiple enhancers, boundary elements, histone modifications and complex physical DNA looping, which are all allele-specific and some of which are species-specific (7,8). Many studies of the \( \text{Igf} \text{2}/\text{H19} \) interval have implicated specific regions of differential DNA methylation as critical for correct allelic expression of these imprinted genes. The mouse \( \text{Igf2}/\text{H19} \) domain is known to contain four differentially methylated regions (DMRs): DMR0 surrounding the region of the placental-specific P0 promoter (9); DMR1, situated 3 kb upstream of promoter P1, a region known to bind the transcription repressor GCF2 (10,11); DMR2, located at the 3'-untranslated region (UTR) of \( \text{Igf2} \) (12,13); lastly, the \( \text{H}1\text{9} \) imprinting control region (ICR) that has been shown to act as a methylation-sensitive boundary, binding the insulator protein CTCF (6,13,14). Sequence analysis has revealed the human \( \text{IGF2}/\text{H19} \) region shares many of the same features, with a few notable exceptions. These include the absence of a human DMR1 and, although both genes are associated with four different promoters, the human gene without a previously reported P0 has an upstream ‘liver-specific’ promoter, which has not been found in the mouse (15).

The expression of the different mouse \( \text{Igf2} \) transcripts is dependent on promoter usage, with P0-derived transcripts only expressed in the labyrinthine layer of the mouse placenta, whereas transcripts from the P1–P3 are found throughout the developing embryo and placenta (9,16). The reported human \( \text{IGF2} \) transcripts (P2–P4) are found in both the developing embryo and the extra-embryonic material, with adult expression limited to P1-derived biallelic transcription in

**Figure 1.** (A) Schematic scale diagram of the mouse \( \text{Igf2}/\text{H19} \) domain on distal mouse Chr 7. The mouse \( \text{Igf2} \) gene comprises multiple transcripts originating from unique promoters, all of which splice into the common protein-coding exons (shaded). The \( \text{H19} \) untranslated gene is located ~72 kb distal of \( \text{Igf2} \) and the \( \text{In} \text{s2} \) gene ~9 kb proximal. Regions of differential methylation are shown, with the filled circles representing methylated and open circles the unmethylated regions. (B) Schematic scale diagram of the human \( \text{INS}, \text{IGF2} \) and \( \text{INSIGF} \) transcripts. CpG islands and the splicing patterns of the sense and anti-sense transcripts are shown. The coding exons are shaded, and the positions of the SNPs are indicated by asterisks. The arrows represent the approximate positions of the RT–PCR primers.
liver (17,18). The IGFII protein has been shown to be a major modulator of fetal and placental growth (19). Elegant gene targeting studies have shown that paternally inherited Igf2 null alleles in heterozygous mice have the same growth restricted phenotype as homozygous null animals (~60% of wild-type weight) (2). Targeted disruption specifically of the mouse Igf2 transcript, by removing the untranslated exon 2, resulted in a milder but still growth-restricted phenotype when compared with the total Igf2 null, even though the fetal promoters (P1–P3) were unaffected and remained transcriptionally active (16). The Igf2-P0 null mice were reported to have a smaller than normal placenta at embryonic day (E)16 of gestation, which was shown to affect the nutrient transfer capacity of the placenta (20). However, once the placental constraints on growth were lifted at birth, postnatal catch-up growth was observed.

In the present study, we have investigated the imprinted expression of the various transcripts of the human IGF2 gene, both in first trimester fetal and placental tissues and term placental material. In addition to the four previously known IGF2 promoters, we describe the expression, imprinting and methylation of three novel transcripts, the human IGF2-P0 promoter/transcript and two INS linked to IGF2 (INSIGF) transcripts and discuss their potential involvement in human development both in utero and in tumourigenesis.

RESULTS

Identification and expression of the human IGF2 -P0 and INSIGF transcripts

Multiple transcripts of human IGF2 are synthesized as a result of alternate promoter usage and splicing of the unique 5′-exons to the 3′-downstream exons encoding the IGFII precursor protein. Promoters P2–P4 are known to be transcriptionally active in many fetal tissues and show a general down-regulation after birth (21). The P1 transcript is unique to humans and incorporates the untranslated exons 1–3. It has been reported that the P1 transcript is expressed from both parental alleles in postnatal liver and fetal choroid plexus/leptomeninges (17). In the mouse, a placenta-specific Igf2 transcript is transcribed from the P0 promoter and incorporates the first two untranslated exons (equivalent to human exons 2 and 3; Fig. 1) that subsequently splice onto the common coding exons. As a consequence of the mouse data with its strong implications as a model for intrauterine growth restriction, we set out to look for a human ‘P0 transcript’. This should potentially incorporate human exon 2 (as the first exon), exon 3 and the common coding exons 7–9.

A 5′-RACE assay of human placental RNA (CTCGCTCA nucleotide 139620 of AC130303) and extending 258 bp into the upstream intron 1 (data not shown). Using various strategies we designed forward primers within this region and reverse primers located within either exon 3 or 7, RT–PCR was used to confirm the 5′-RACE data. This demonstrated that the human IGF2-P0 transcript initiation site is located 5′ to the splice donor site of the P1 transcript’s exon 2 and that this 5′-UTR sequence is unique to the human IGF2-P0 transcript.

Northern blotting has previously shown that the mouse Igf2-P0 transcript is solely expressed in the placenta, whereas in situ hybridization shows that it is specifically restricted to the labyrinthine layer (9,16). To assess the expression of the human IGF2-P0 transcript, we hybridized an adult multi-tissue northern blot with an anti-sense riboprobe corresponding to the unique 5′-IGF2-P0 sequence reveals a single band of ~5 kb in all tissues. The same blot was reprobed with an anti-sense riboprobe corresponding to IGF2 exon 2. The ubiquitously expressed IGF2-P0 transcript was detected, as was the liver-specific P1 transcript and the short INSIGF transcript in pancreas. The blot was hybridized with a human GAPDH cDNA fragment to ensure equal sample loading. (B) Fetal northern blots hybridized with the IGF2-P0 and exon 2 riboprobes reveal expression limited to skeletal muscle. The same blots were subsequently rehybridized with an IGF2 exons 8 and 9 riboprobes to detect all IGF2 isoforms and a β-Actin probe to ensure equal loading.

![Figure 2](http://hmg.oxfordjournals.org/)
during early development, we hybridized a northern blot containing selected first and second trimester tissues samples with the same P0-specific riboprobe. In contrast to the mouse, this revealed that the expression of the IGF2-P0 transcript is not detectable in early placenta but is most abundant in fetal skeletal muscle (Fig. 2B). The same adult and fetal northern blots were then sequentially re-hybridized with riboprobes specific to IGF2 exon 1, exon 2 and a fragment encompassing exons 8 and 9 in order to detect expression of other IGF2 transcripts. The IGF2 exon 2 riboprobe revealed ubiquitous expression of the IGF2-P0 transcript in adult tissues (except brain) as well as the slightly larger IGF2-P1 transcript in liver.

Interestingly, the exon 2 riboprobe revealed an ~1.5 kb pancreas-specific band that was not detected when using either the P0-specific or P1-specific riboprobes (Fig. 2A). From the investigation of expressed sequence tag (EST) databases, we suspected that this band might result from a novel transcript originating from the INS promoter and splicing to IGF2 exon 2 (EST transcript accession nos ig76F01/ BM312593 or ir36b02/CA866245). ESTs for this transcript were pancreas-specific and consist of INS exons 1 and 2, which splice on to IGF2 exons 2–4. In addition, a precisely matching protein sequence (XP_508220) has been predicted by the computational GNOMON method in the Pan troglodytes genome. We have named this transcript INSIGF. As the transcript lacks INS exon 3 and the usual stop codon, the open reading frame differs from that of INSULIN and extends into the IGF2 exon 3. Translation of this ORF would result in a novel protein that not only includes the INSULIN leader sequence and B-chain peptide but also an additional peptide at the C-terminal end. Analysis of the Prodom and Pfam databases does not detect any other known protein motifs within this amino acid translation. Subsequent RT–PCR amplifications revealed that a longer splice variant, which includes INS exons 1 and 2 and IGF2 exons 2, 3, 7, 8 and 9 (transcript accession no. DQ104205), also exists. This transcript is bicistronic, with the open reading frames present for both the novel INSIGF protein and IGFII (Fig. 1B). Both transcripts of INSIGF show a restricted expression profile when analysed by RT–PCR. Primers within exon 1 of INS and exon 3 of IGF2 (detecting both INSIGF transcripts) show expression restricted to pancreas, eye and limb. However, the specific amplification of the short INSIGF isoform using a reverse primer in IGF2 exon 4 detected products only in pancreas and eye (Fig. 3).

Mouse Insigf transcripts

Investigation of a potential mouse Insigf sequence has failed to identify a transcript by RT–PCR, northern blotting or interrogation of dbEST. Nevertheless, the alignment of the mouse and human genomic sequences reveals significant homology corresponding to the exons and exon–intron boundaries, at least up to and including the mouse untranslated exon u2. Translation of this putative transcript would result in a protein similar to the human INSIGF. The conceptual protein translations, however, differ near the C-terminal ends where the mouse sequence incorporates a 27 bp imperfect tandem repeat sequence. With no stop codon present until after this sequence, 194 amino acids based on the PEPRPEPPK repeat motif would be added (Fig. 4).
Characterization of the human IGF2-P0 promoter

Analysis of the 5'-RACE products for the IGF2-P0 transcript revealed a consensus sequence (PyPyAN(T/A)PyPy) for an initiator element (Inr element). Inr promoter elements are generally found to encompass transcription start sites in eukaryotic promoters and in particular TATA-less promoters. To measure IGF2-P0 promoter activity, we utilized a transient luciferase expression assay in a human-term extravillous trophoblast cell line (Tc11) (22). A 552 bp fragment immediately upstream of the first exon and including the putative IGF2-P0 5'-UTR was cloned into pGL3 reporter constructs both with and without a SV40 enhancer. This enhancer is known to stimulate the transcription of many eukaryotic promoters in vitro. The promoter activity was measured using the firefly luciferase reporter gene and normalized for transfection efficiency against the co-transfected Renilla luciferase reporter plasmid (TK-Renilla luciferase). Promoter activity of P0 constructs in replicate experiments relative to a positive control (pGL3-promoter) is shown in Figure 5. The Tc11 cells showed weak activity for the human P0 promoter (pP0 construct), which increased significantly when associated with the SV40 enhancer (P0–Enh construct). In fact, the luciferase activity detected with the P0–Enh construct is close to the corresponding value obtained for the positive pGL3-promoter control (SV40-promoter activity) and is significantly stronger than that of the pP0 construct and the pGL3–Enh vector (the enhancer only, no promoter control). The significant difference between reporter activities between the pP0–Enh construct and the pGL3–Enh vector is due to the presence/absence of the promoter sequence and confirms that the region cloned has promoter activity in vitro. The promoter activity reported for the mouse Igf2-P0 and P3 promoters in Tc11 cells is greater than the values obtained for human IGF2-P0 promoter, which corresponds to the higher transcription levels observed in vivo (Constancia and Murrell, unpublished data) (23).

Promoter-specific imprinting of the human IGF2-P0 transcript

The various transcripts originating from the IGF2 promoters were analysed for imprinted expression in human, using the RT–PCR approach. Thirty-term placenta and 18 fetal samples sets with corresponding parental blood samples were genotyped for both the Alu1 SNP in exon 3 (rs17881514) and the Apa1 SNP in the 3'-UTR of IGF2.
Using both strand-specific (to avoid amplification of the paternally expressed IGF2-AS/PEG8) and random-primed cDNA, all heterozygous sample sets clearly showed that the expression from each individual IGF2 promoter (P0–P4) was monoallelic, and in informative sample sets, this expression was derived from the paternal allele [three sample sets using rs17881514 (Fig. 6) and four sample sets using rs680 (data not shown)]. As the expression of the mouse Igf2-P0 transcript is labyrinthine-specific, we also analysed the imprinting of the human IGF2-P0 transcript in the first trimester (n = 2) and term (n = 2) cytokeratin 7-enriched villous trophoblasts. These are the human cells equivalent to the mouse villous trophoblast cells contained within the labyrinthine zone (24). Paternal expression of the human IGF2-P0 transcript was also observed in these cells.

**Imprinting of the INSIGF transcripts**

The imprinting status of the INSIGF transcripts was studied in 20 normal adult pancreas samples and the same 18 fetal sample sets previously used to analyse the IGF2 imprinting. DNAs from these samples were also genotyped for a Pst1 SNP in exon 3 of INS (rs3842757). Two pancreas samples were heterozygous for the rs17881514 and rs3842757 SNPs and were biallelic for INS, INSIGF and IGF2-P0 (Fig. 6). Interestingly, both INSIGF isoforms were monoallelic/paternally expressed in eye (n = 3) and limb samples (n = 1) (Fig. 6).

**IGF2 methylation profile**

Many studies have implicated DNA methylation throughout the IGF2/H19 region as critical for correct tissue-specific imprinting of the various IGF2 transcripts (10–12). We, therefore, analysed all CpG islands within the IGF2 genomic region, as well as the region surrounding the promoter of the human IGF2-P0 transcript (Fig. 7). Each region was analysed by treating genomic DNA from various tissues with sodium bisulphite, followed by PCR amplification that would include both methylated and unmethylated molecules. Resulting products were subjected to COBRA (combined bisulphite restriction analysis) (25) or cloned and sequenced.
The first CpG island maps between the first two untranslated exons that comprise the human P1 transcript and is 1.8 kb downstream of two ALU repeat elements. Using bisulphite mutagenesis and PCR on treated DNA from placenta, liver, kidney and lymphocytes, this CpG island was found to be fully methylated on both alleles in all tissues. The second and third CpG islands map to the promoter regions of P2–P4 and the IGF2-AS (PEG8) transcripts, essentially representing a single large CpG island. Two independent, non-overlapping PCR products revealed that this region was fully unmethylated in all tissues. The final CpG island maps to exon 9. Using Southern blot analysis, this region has previously been defined as a DMR in both human and mouse, with the paternal allele being more methylated than the maternal allele (10). However, the differential methylation of this region is disputed because detailed studies utilizing bisulphite analysis have revealed a mosaic methylation profile (26). Our results also show that the methylation profile for this region is not uniform and that tissue-specific differences in methylation exist (Fig. 7).

The region surrounding the mouse P0 promoter is a maternally methylated DMR in placenta, even though it is not statistically defined as a CpG island (9). The equivalent genomic region surrounding human exon 2 also fails to meet the criteria for a CpG island. Nevertheless, differential methylation for this region has previously been reported, and hypomethylation is associated with the loss of imprinting (LOI) of IGF2 in cancers (27–29). We analysed two regions within this interval, one overlapping with the human P0 promoter, which contains eight CpG dinucleotides, and the other between exons 2 and 3, incorporating the same CpG dinucleotides described by the Feinberg group (29). Both regions contained both fully methylated and unmethylated PCR products in all tissues analysed, indicating that the differential methylation of this region

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**Figure 7.** (A) A schematic diagram of the human IGF2 gene showing the relative positions of the promoters and CpG islands. (B) Restriction digestion of PCR products generated from bisulphite-treated DNA from human fetal tissues. All unmethylated C nucleotides should be converted to T nucleotides during the treatment. The restriction-enzyme recognition sequences for \( \text{Taq}1 \) (TCGA) and \( \text{Tai}1 \) (ACGT) will be only present in methylated DNA because methylated CpG dinucleotides are resistant to conversion. PCR products from CpG1 are completely digested by \( \text{Taq}1 \), indicating that this CpG island is fully methylated. The two PCR products from the P0 promoter region (DMR0) clearly have equal representation of digested and undigested molecules, indicating that this region is differentially methylated. The CpG2 and CpG3 PCR products are resistant to digestion with \( \text{Taq}1 \), indicating that these regions are fully unmethylated. Lastly, the CpG4 PCR products show a tissue-specific differential methylation pattern. (C) Subsequent cloning and sequencing of the various bisulphite PCR products from treated placenta DNA confirm the methylation profiles. Only the 3′-most CpG dinucleotides are shown for CpG3; however, all 50 CpG dinucleotides within the PCR product are unmethylated. The arrows represent the position of the \( \text{Taq}1 \) or \( \text{Tai}1 \) restriction sites within the PCR products. (D) The complete lack of methylation at DMR0 (2) in a patient with pUPD11.
is not limited to extra-embryonic material as seen in the mouse. Further analysis of PCR products obtained from bisulphite-treated pUPD11 DNA confirmed that the human P0 transcript is embedded within a maternally methylated DMR (Fig. 7D).

DISCUSSION

The paternal expression of IGF2 gene is regulated in a development-dependent and tissue-specific manner. Previously, the expression of IGF2 in the fetus was thought to arise from four different promoters, utilizing alternative splicing and polyadenylation signals (15). Although P2, P3 and P4 promoters have counterparts in the rodent, the P1 promoter is unique to humans (18). Recently, a placental-specific transcript originating from the P0 promoter in mouse was discovered and investigated by the generation of a knockout (9,16). Paternal transmission of the P0 null allele resulted in a severe growth restriction of the placenta at E12, leading to fetal growth restriction at E18 due to disrupted nutrient transfer across the mouse labyrinthine layer (16,20). As the mouse Igf2-P0 transcript has a major effect on controlling growth and function of the placenta, we undertook an investigation to see whether such a mechanism is conserved in humans. We successfully identified a human equivalent to the mouse IGF2 transcript originating from the P0 promoter in mouse was discovered and investigated by the generation of a knockout (9,16).

Even though the human and mouse P0 transcripts originate from similar regions and have identical splicing patterns, there are subtle differences between species. The mouse Igf2-P0 transcript is expressed exclusively in the placenta and is specifically detected in the labyrinthine trophoblast layer (16). In contrast, the human fetal IGF2-P0 transcript is expressed at high levels in fetal skeletal muscle and later, at a lower transcribed level, it is found ubiquitously in adult tissues and term placenta. This marked change in spatial expression may result from the epigenetic differences we found between species in the P0 promoter regions. The paternal expression of the Igf2-P0 transcript in the mouse originates from the only site of maternal allele methylation in the Igf2 locus. This maternal methylation is limited to extra-embryonic material, suggesting that the transcriptional silencing of the maternal allele may be controlled by promoter methylation (9). However, maternal methylation was observed in all human tissues, which correlates with maternal repression of the human IGF2-P0 transcript in the adult tissues.

It is not currently known whether the promoter methylation alone at the human DMR0 is sufficient to bring about maternal silencing of the P0 promoter, independent of the other IGF2 promoters. Although it would have been of great interest to investigate the imprinting status of the IGF2-P0 transcript in relation to the other IGF2 transcripts in BWS fibroblasts with H19 DMR hypomethylation, the IGF2-P0 transcript is not expressed in the available adult cell lines tested (data not shown). Nevertheless, evidence that the DMR0 plays a critical role in the regulation of IGF2-imprinted expression has come from the observation that this region is hypomethylated in Wilms’ tumour and that colorectal cancers are associated with the reactivation of the maternal allele of IGF2 (27–29). Indeed, other groups have proposed that the human DMR0 is a methylation-dependent silencer element that may be regulating IGF2 expression independent of the H19 DMR (29). It is, therefore, possible that the human P0 transcript has a role to play in cancer. If LOI of IGF2-P0 was found in cancerous tissues, specifically colorectal cancer with loss of methylation DMR0, it could act independently of the other IGF2 isoforms that are mainly expressed and imprinted in the fetus. It remains to be studied whether the human IGF2-P0 transcript becomes biallelic in tumours and whether this over-expression might aid the overgrowth in these tumours (27,28).

We also report here our evidence for two novel transcripts originating from the INS promoter. Both contain a novel ORF altering the normal INSULIN protein. It is not yet clear whether this protein is translated in vivo and requires further studies to examine its potential function. The transcripts are biallelically expressed in pancreas, which would be expected because INS, sharing the same promoter, is also biallelic in this tissue. However, similar to INS that shows evidence of tissue-specific imprinting in the yolk sac and possibly also the thymus (30,31), INSIGF transcripts are monoallelically/paternally expressed in the limb and eye.

There may be interesting implications for a mouse Insigf transcript because the previously reported Igf2-P0 knockout mouse removes sequences potentially common to both transcripts. However, we can find no evidence for the expression of this sequence in the mouse. Also, the conceptually translated mouse Insigf protein is different than that of the human/monkey because of the presence of an additional simple sequence repeat found in the mouse un2 exon. This encodes a proline-rich insertion likely to render it non-functional.

Here, we have identified and characterized the human IGF2-P0 transcript as well as two novel imprinted transcripts running from INSULIN into IGF2. The human IGF2-P0 transcript is unlikely to have the same role in fetal growth as it does in the mouse because it is found in different tissues and is not specific to the placenta. However, it has a clear imprinted expression pattern in adult tissue, and we speculate that it may play a role in growth regulation due to LOI in adult cancers. Similarly, the two novel INSIGF-imprinted transcripts generated from this important locus also merit further study for their possible role in normal development and disease.

MATERIALS AND METHODS

Collection of human material

A total of 18 fetal tissue sets (8–18 weeks) with first trimester placental samples and corresponding maternal blood samples were obtained from the termination of pregnancies at Queen Charlotte’s and Chelsea Hospital. Samples were washed in sterile PBS and processed. Local ethical approval for obtaining
fetal tissues was granted by the Research Ethics Committee of Hammersmith, Queen Charlotte’s and Chelsea and Acton Hospitals Research Ethics Committee (2001/6028). Thirty placental trio samples consisting of multiple site placental tissues with corresponding maternal and paternal blood samples were collected from consecutive consenting pregnancies at Queen Charlotte’s and Chelsea Hospital (local ethics approval 2001/6029). Twenty histologically normal adult pancreatic samples (20–46 years) were obtained from the MRC tissue bank at Hammersmith Hospital and University Hospital Heidelberg. The collection of pancreatic samples was approved by the Ethical Committee of the University of Heidelberg. Written informed consent was obtained from all patients.

**Imprinting assays**

For the imprinting analysis of IGF2, INSIGF and INS, an RT–PCR approach was used as described previously (33,34). For IGF2, each individual isoform of IGF2 was amplified using a promoter-specific forward primer in conjunction with a common IGF2 3'-UTR reverse primer incorporating the Apal SNP in the PCR product. The following promoter-specific forward primers were used: P1-CTCGCAGGGTTGAGACAG; P0 (EF)-GTAAAACCATACTTCTAGTTGGCATT; P2-CTTCAGGTGATTGGTCCCCATC; P3-GGACAATCACGAGATTTCTCC; P4-CTTCCTCGTAGAAGAGAC TACC and IGF2 3'-UTR R-CTTTTTAAGGAGAATGAG. The products were subsequently sequenced using the IGF2 Apal F as a nested sequence primer. The imprinting of the IGF2-P1 and P0 transcripts was also confirmed using the promoter-specific forward primer and an IGF2 exon 3 R-GCTGAGCTGCCAGCAGTACAG, incorporating the AluI SNP in the PCR product. The imprinting of the INS gene utilized an INS Ex1 F-CTGACATAAGAGGGCCAC and INS Ex3 R-GTTCGAAGGCCCTTCCATC. The imprinting of the shorter INSIGF used INS Ex1 F and IGF2 Ex4 R-GACACCTTGAGAAGACACTCCC. All RT–PCRs used HotStar Taq DNA polymerase (Qiagen), following manufacturer’s instructions, and products were subjected to both restriction enzyme digestion and directly sequenced in both orientations using an ABI prism 3100 DNA sequencer (Applied Biosystems).

**Northern blotting**

To analyse relative expression levels of IGF2-P0 in adult tissues, a multiple human blot (FirstChoice) containing polyA + RNA (2 μg per lane) was purchased from Ambion. Custom-made fetal northern blots were obtained from Biochain. The IGF2 RNA probes, which encompassed the P1-specific promoter region (130501–130800 of AC0130303), P0-specific promoter region (139201–139620 of AC0130303) or the coding sequence of IGF2, were radiolabelled with [32P]UTP using the T7/SP6 MAXIscript in vitro transcription kit (Ambion). Hybridizations were carried out overnight at 65°C and washed according to manufacturer’s instructions. The GAPDH or β-actin PCR probe was used to confirm equal loading of RNA in each lane.

**Luciferase promoter assay**

Luciferase assays for IGF2 promoter activity were carried out as described previously (23), using the Promega Dual Luciferase assay kit and the luciferase pGL3 reporter vectors and Qiagen Effectene reagents. The P0 promoter construct was made by amplifying bases 139039–139638 (AC130303) using the following primers: forward 5'-GCTAGGTACCCTTGCTCAGTG AGAGTGG-3' and reverse 5'-TCAGGATCCAGCTAGGCC TGGAGAAACG-3'. These primers contained restriction sites at their 5'-ends (Fwd, Kpn1; Rev, BamHI) so that the PCR product could be directly cloned into multiple cloning site of the pGL3 vectors.
Methylation analysis by bisulphite sequencing

Approximately 1 μg DNA was treated with sodium bisulphite as described previously (35). For the bisulphite treatment of trophoblast DNA, ~1000 cells were resuspended in 32.5 μl of solution containing 10 μg glycogen, 1 mM SDS and 280 μg/ml proteinase K, incubated for 90 min at 37°C, followed by 15 min at 96°C in a thermocycler. This lysate was used directly for bisulphite treatment. HotStar DNA polymerase (Qiagen) was used to amplify CpG island products amplified and unmethylated CpG dinucleotides to control for any potential cloning bias.

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Conflict of Interest statement: None declared.

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