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(54) Title: FRIZZLED PROTEINS AND DETECTION AND TREATMENT OF CANCER

(57) Abstract: The present specification provides, inter alia, methods of using Wnt and FZD proteins, genes, FZD and Wnt-specific antibodies and probes in diagnosis and treatment of cancer and for screening test compounds for an ability to treat cancer. Also disclosed are compounds useful for treating cancer such as liver cancer.



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Frizzled Proteins and Detection and Treatment of Cancer

STATEMENT AS TO FEDERALLY SPONSORED RESEARCH

This invention was made with Government support under National Institutes of Health Grant Nos. CA035711, AA002666, and AA008169. The Government has
5 certain rights in this invention.

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application
10 No. 60/611,919, filed September 21, 2004, which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

This invention relates to detection and treatment of liver cancer.

BACKGROUND

15 Hepatocellular carcinoma (HCC) is the major primary malignant tumor of the liver. Although viral etiological factors have been identified, the molecular mechanisms that contribute to tumor progression during hepatocarcinogenesis remain largely unknown. The Frizzled family of proteins is composed of ten or more seven-transmembrane proteins that act as receptors for Wnt proteins. The Wnt/Frizzled
20 signaling network influences diverse biological processes ranging from cell fate determination to cell motility and proliferation.

β -catenin is a multifactorial protein with a role in cell-cell adhesion that involves strengthening the linkage of cadherin and α -catenin to the actin cytoskeleton. In the absence of Wnt/Frizzled signaling, β -catenin is phosphorylated by interactions
25 with glycogen synthase kinase (GSK)-3 β , and forms a complex with axin and the adenomatous polyposis coli protein (APC). Subsequently β -catenin is targeted for degradation by the ubiquitinproteasome system. In contrast, binding of a Wnt ligand to its Frizzled receptor stabilizes intracellular β -catenin through the inhibition of
30 GSK-3 β enzymatic activity. Subsequently, β -catenin translocates into the nucleus in association with high mobility group domain factors such as Tcf/Lef. This complex is

associated with transcriptional up-regulation of growth regulatory and cell migration related genes.

SUMMARY

The present invention is based, in part, on the discovery that Frizzled 7 (FZD7) is commonly overexpressed, and Frizzled 8 (FZD8) is commonly underexpressed, at the mRNA and protein level, in many HCC, for example hepatitis B virus (HBV) related HCC. Liver cancer cells that overexpress FZD7 exhibit enhanced cell motility and migration. Overexpression appears to be an early event during the multi-step process of hepatocyte transformation. Accordingly, FZD7 is a novel molecular target for therapy of liver cancer.

Accordingly, in one aspect, the invention provides a method of determining whether a cell (e.g., a liver cell) is, or is at risk for becoming, a cancer cell. The method includes (a) providing a test cell (e.g., a liver cell); (b) determining whether the cell's level of FZD7 expression is higher, or FZD8 expression is lower, than that of a control cell; and (c) classifying the test cell as (i) a cancer cell or (ii) at risk for becoming a cancer cell, if the test cell's level of FZD7 expression is higher, or the test cell's level of FZD8 expression is lower, than that of the control cell. Where the method includes determining the cell's level of FZD7 expression, the method can further include: (c) determining whether the test cell's level of FZD8 expression is lower than that of a control cell, wherein a lower level of expression of FZD8 indicates that the test cell is, or is at risk for becoming, a cancer cell. Where the method includes determining the cell's level of FZD8 expression, the method can further include: (c) determining whether the test cell's level of FZD7 expression is higher than that of a control cell, wherein a higher level of expression of FZD7 indicates that the test cell is, or is at risk for becoming, a cancer cell.

In another aspect, the invention provides a method of determining whether a patient is suffering from or at risk for cancer, e.g., whether a test tissue sample comes from a patient that is suffering from or at risk for cancer. The method can include: providing a test tissue sample (e.g., a liver tissue such as tumorous or peritumorous liver tissue) obtained from a patient, and (b) determining whether the level of FZD7 expression is higher, or whether the level of FZD8 expression is lower, in the test tissue sample than that in a comparable tissue sample obtained from a healthy individual,

wherein a higher level of expression of FZD7 or a lower level of expression of FZD8 in the test tissue sample is an indication that the sample is from a patient suffering from or at risk for cancer. Where the method includes determining the level of FZD7 expression, the method can further include: (c) determining whether the level of FZD8 expression in the test tissue sample is lower than that in a tissue sample obtained from a healthy individual, wherein a lower level of expression of FZD8 is an indication that the sample comes from a patient is suffering from or at risk for cancer. Where the method includes determining the level of FZD8 expression, the method can further include: (c) determining whether the level of FZD7 expression in the test tissue sample is higher than that in a tissue sample obtained from a healthy individual, wherein a higher level of expression of FZD7 is an indication that the patient is suffering from or at risk for cancer.

In any of the methods described herein, determining the level of FZD7 or FZD8 expression can include determining the amount of FZD7 or FZD8 mRNA in the cell, e.g., using a Northern blot assay or an RT-PCR assay. In other embodiments, determining the level of FZD7 or FZD8 expression can include determining the amount of FZD7 or FZD8 protein in the cell, e.g., using an antibody, e.g., an antibody that binds to SEQ ID NOS:32 or 55.

In still another aspect, the invention includes a method of treating cancer (e.g., liver cancer) in a patient. The method includes administering to the patient an effective amount of a compound that reduces Wnt/ FZD7 signaling in FZD7-expressing cells of the patient and that is optionally non-lethal to the FZD7-expressing cells. The compound can be a compound that reduces FZD7 expression in the patient, e.g., an antisense oligonucleotide, a double stranded RNA (dsRNA) that includes a nucleotide sequence that hybridizes under physiological conditions to a FZD7 nucleotide sequence, an isolated FZD7 receptor or a Wnt binding fragment thereof, and/or a genetic construct encoding a truncated form of FZD7 (e.g., a form of FZD7 lacks FZD7's intracellular and/or transmembrane domain). The compound can be administered by any route, e.g., by administration to the patient's liver.

In yet another aspect, the invention includes a method of reducing motility in a cancer cell. The method includes administering to the cell an effective amount of a compound capable of reducing Wnt/FZD7 signaling in the cell and which is optionally non-lethal to the cell. The compound can be a compound that reduces expression of

FZD 7 in the cell, e.g., an antisense oligonucleotide, a double stranded RNA (dsRNA) that includes a nucleotide sequence that hybridizes under physiological conditions to a FZD7 nucleotide sequence, an isolated FZD7 receptor or a Wnt binding fragment thereof, and/or a genetic construct encoding a truncated form of FZD7 (e.g., a form of FZD7 lacks FZD7's intracellular and/or transmembrane domain).

In another aspect, the invention includes the use of a compound that reduces Wnt/ FZD7 signaling in FZD7-expressing cells in the manufacture of (i) a medicament for the treatment of liver cancer or (ii) a medicament that reduces the motility of liver cancer cells. Optionally, the medicament is non-lethal to FZD7 expressing cells. The medicament can be manufactured using a compound that reduces FZD7 expression in the patient, e.g., an antisense oligonucleotide, a double stranded RNA (dsRNA) that includes a nucleotide sequence that hybridizes under physiological conditions to a FZD7 nucleotide sequence, an isolated FZD7 receptor or a Wnt binding fragment thereof, and/or a genetic construct encoding a truncated form of FZD7 (e.g., a form of FZD7 lacks FZD7's intracellular and/or transmembrane domain).

In still another aspect, the invention includes a transgenic, animal, e.g., a non-human animal, whose genome comprises a *c-myc* transgene and an IRS-1 transgene, wherein the animal exhibits increased susceptibility to hepatocellular carcinoma, as compared to a wild type counterpart. The animal can be a mammal, e.g., a primate, pig, rodent (e.g., mouse or rat), rabbit, cow, horse, cat, dog, sheep or goat. The transgenic animal can develop precancerous hepatocyte dysplasia in less than about 90 days from birth, e.g., in less than about 60 days from birth.

In another aspect, the invention includes a method of making a transgenic animal, e.g., a non-human animal, susceptible to HCC. The method includes: (a) crossing a first parental non-human animal whose genome comprises a *c-myc* transgene that is expressed in hepatic cells with a second parental animal whose genome comprises a IRS-1 transgene that is expressed in hepatic cells; and (b) isolating a progeny animal that expresses the transgenes of both parental animals and is a transgenic animal susceptible to HCC. The animal can be a non-human mammal, e.g., a primate, pig, rodent (e.g., mouse or rat), rabbit, cow, horse, cat, dog, sheep or goat.

In yet another aspect, the invention includes a method of identifying a compound for treating liver cancer. The method includes: (a) administering a test compound to a transgenic animal described herein; and (b) determining whether the

compound reduces the incidence or level of liver cancer in the transgenic animal. A Compound identified by a method described herein can be used in the manufacture of a medicament for (i) the treatment of liver cancer or (ii) reducing motility of a liver cancer cell.

In still another aspect, the invention includes a method of identifying an anticancer agent. The method includes: (a) administering a test compound to a cell; and (b) determining whether the compound reduces Wnt/FZD7 signaling in the cell, wherein a compound that reduces Wnt/FZD7 signaling is a candidate anticancer agent. The cell of step (a) can be, for example, a liver cell. Step (b) can be performed, for example, by (i) determining whether the compound reduces expression of FZD7 in the cell, (ii) detecting the amount of FZD7 mRNA in the cell, or (iii) detecting the amount of FZD7 protein in the cell. The method can further include: (c) determining whether the candidate anti-cancer agent is capable of: (i) reducing cancer cell motility; (ii) reducing β -catenin accumulation in a cancer cell; or (iii) treating cancer *in vitro* or *in vivo*; wherein a candidate that is capable of at least one of these is an anti-cancer agent. A compound identified by a method described herein can be used in the manufacture of a medicament for (i) the treatment of liver cancer or (ii) reducing motility of a liver cancer cell.

In another aspect, the invention includes a method for identifying an anti-cancer agent. The method includes: (a) providing a polypeptide comprising the amino acid sequence of a FZD7 receptor protein or a fragment thereof; (b) contacting the polypeptide with a test compound; (c) detecting binding between the polypeptide and the test compound; (d) selecting the test compound if it binds to the polypeptide; and (e) determining whether the selected compound (i) reduces Wnt/FZD7 signaling in a cell that expresses FZD7, (ii) reduces motility of a cancer cell, (iii) reduces β -catenin accumulation in a cancer cell; or (iv) can be used to treat cancer *in vitro*, or *in vivo*, wherein a test compound that reduces does any one or more of a (i)-(iv) is an anti-cancer agent. The polypeptide of (a) can be a naturally occurring polypeptide or a recombinant polypeptide. The polypeptide can include SEQ ID NO:2, e.g., along with at least one non-FZD7 sequence. The polypeptide can be provided as a polypeptide expressed on the surface of a cell or as an isolated polypeptide. Compounds identified by this method can be used in the manufacture of a medicament for (i) the treatment of liver cancer or (ii) reducing motility of a liver cancer cell.

In another aspect, the invention include the use of any of the compounds described herein (e.g., candidate anti-cancer agents and/or anti-cancer agents) (a) for the treatment of liver cancer or (b) in the preparation of a pharmaceutical composition for treatment or prevention of a condition described herein, e.g., cancer, e.g., liver cancer. The composition can be used in a method for treating cancer in accordance with the methods described herein. The composition can be in any form described herein, e.g., a liquid or solid composition.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. Suitable methods and materials are described below, although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention. All publications, patent applications, patents, and other references mentioned herein are incorporated by reference in their entirety. In case of conflict, the present specification, including definitions, will control. The materials, methods, and examples are illustrative only and not intended to be limiting.

Other features and advantages of the invention will be apparent from the following detailed description, and from the claims.

DESCRIPTION OF DRAWINGS

Figs. 1A-1C are graphs that illustrate the results of a real time PCR assay for Frizzled-7 gene. Closed diamonds represent the standard curves for *18S rRNA* (Fig. 1A) and *FZD7* (Fig. 1B). Open diamonds represent mean values of unknown HCC tumor samples performed in duplicate. The standard curves show a 5 order of magnitude linear dynamic range. Fig. 1C: The *FZD7* mRNA steady state levels in HCC cell lines expressed as relative abundance of *FZD7* mRNA. The value represents the mean $\pm$ SD from 3 separate experiments.

Figs. 2A-2B are graphs that illustrate measurements of HCC cell motility. Fig. 2A: the percent of non-migrated, and total migrated (migrated-adherent, and migrated non-adherent) cells were evaluated by a luminescent based assay. The values (percent of cells) are expressed as mean $\pm$ SD from 6 separate measurements. *t*-test, **p* < 0.01, ***p* < 0.001 as compared to values obtained with HepG2 cells. Fig. 2B: Correlation between *FZD7* mRNA steady state levels and the percent of total migrated

cells (both migrated-adherent and migrated-non-adherent). Z-test of correlation, $p = 0.02$.

Figs. 3A-3C are Western blots and a graph illustrating an analysis of total cellular β -catenin and Tcf reporter assay. There is no correlation of PCNA with *FZD7* mRNA (Fig. 3A). However, high levels of *FZD7* gene expression are associated with nuclear accumulation of β -catenin; lower *FZD7* expression levels were associated with both nuclear and cytoplasmic accumulation in HepG2 and Hep3B cells (Fig. 3B). Fig. 3C illustrates measurements of a Tcf transcriptional activity. The HCC cell lines were co-transfected with either TOPflash (■) or FOPflash (□) and β -galactosidase expressing plasmid. Note the high level of Tcf mediated transcription activity in all three cell lines. There was a general correlation between *FZD7* levels and Tcf transcriptional activity.

Figs. 4A-4E are diagrams, graphs and Western blots illustrating construction and expression of *FZD7* mutant proteins. Fig. 4A: *FZD7-FL*: wild-type full-length *FZD7* protein; *FZD7- ΔC* : *FZD7* protein truncated in the intracellular domain; *FZD7- $\Delta T\Delta C$* : secreted *FZD7* protein truncated in both the transmembrane and intracellular domains; CRD: cystein rich domain. The Wnt-ligand interacts with the CRD of *FZD7* and with the epidermal growth factor repeat (EGFR) regions 1 and 2 of LRP5/6 as represented by grey boxes. Fig. 4B: a bar graph illustrating expression in a heterogenous population of Huh7 cells stably transfected with pcDNA3/*FZD7- $\Delta T\Delta C$* or pcDNA3/empty vector as a control. Expression was assessed by quantitative real-time RT-PCR with either a first set of primers located in the extracellular domain, or a second set located in the intracellular domain of *FZD7* receptor. Expression levels were normalized to the values obtained with pcDNA3. Fig. 4C: Western blot illustrating expression of *FZD7- $\Delta T\Delta C$* as assessed using the monoclonal anti-M2 flag tag antibody in a heterogenous population of Huh7 cells stably transfected with *FZD7- $\Delta T\Delta C$* or pcDNA3/empty vector. Fig. 4D: a bar graph illustrating expression of various forms of *FZD7* in Huh7 cells. Cells were stably transfected with pLenti6/V5-GFP clone-4 (GFP-C4) served as a negative control; Huh7 cells stably transfected with pLenti6/V5-*FZD7- ΔC* clones-1 to 8 (ΔC -C1 to C8); Huh7 cells transiently transduced with pLenti6/V5-*FZD7- ΔC* (ΔC -Tr). Huh7 cells stably transduced with pLenti6/V5-*FZD7-FL* clone-1

(*FL-C1*) served as positive controls for RT-PCR assessment with sets of primers targeting either the extracellular domain or the intracellular domain of *FZD7* receptor. Expression levels were normalized to the values observed with pLenti6/V5-GFP-C4. Fig. 4E: Western blot analysis of expression of *FZD7-ΔC* using rabbit polyclonal anti-human *FZD7* antibody with or without immunoprecipitation with a goat anti-human V5 antibodies coupled to agarose beads. Experiments were performed in Huh7 cells transduced with pLenti6/V5-*FZD7-ΔC* and pLenti6/V5-GFP-C4 as a negative control.

Figs. 5A-5D are Western blots and graphs illustrating β -catenin protein levels in HCC cells after ectopic expression of a dominant negative *FZD7-ΔTΔC* mutant receptor expressing construct. Fig. 5A: Western blots illustrating the levels of β -catenin protein in Huh7, Focus, Hep3B, and HepG2 HCC cell lines transfected with the secreted form of the *FZD7-ΔTΔC* receptor. Fig. 5B: Western blot illustrating the level of β -catenin protein in Huh7 cells following transduction with the transmembrane *FZD7-ΔC* mutant receptor cloned into pLenti6/V5. Fig. 5C: bar graph illustrating the motility of Huh7 cells toward soluble collagen-I under conditions of transient transfection with pLenti6/V5-*FZD7-ΔTΔC*, pLenti6/V5-*FZD7-ΔC*, or pLenti6/V5-GFP as a control. Fig. 5D: bar graph illustrating motility measurements of representative clones under conditions of stable integration and expression of: C1 = *FZD7-ΔTΔC*; C5 = *FZD7-ΔC*, and C6 = *FZD7-ΔC*. The percent of non-migrated, and total migrated (migrated-adherent, and migrated non-adherent) cells were evaluated by a luminescent-based assay after 3 hours at 37°C. The values (percent of cells) expressed as mean $\pm$ SD, are from 6 separate measurements. t-test, * $p < 0.05$, ** $p < 0.01$ when compared with GFP negative control.

Figs. 6A-6B are a diagram and bar graph illustrating β -catenin constructs and the results of a cell motility assay. Fig. 6A: an illustration of the β -catenin constructs. Approximate location of functional domains: black, protein instability; right-leaning hatch, N-terminal transactivation domain; left-leaning hatch, C-terminal transactivation domain; grey, armadillo repeats, protein-protein interaction. Fig. 6B: a bar graph illustrating motility measurements of *FZD7-ΔC*-C6 and *GFP-C4* blasticidin-selected clonal Huh7 cell populations initially transduced with pLenti6/V5-D-TOPO[®] lentiviral vectors expressing either the *FZD7-ΔC* negative dominant mutant or *GFP* as

control, and co-transduced once again with a pLenti6/V5-D-TOPO[®] lentiviral vector expressing a biologically active $\Delta N/\Delta C$ β -catenin mutant or GFP to keep constant the total amounts of plasmid DNA. The percent of non-migrated and total migrated (migrated-adherent, and migrated nonadherent) cells were evaluated by a luminescent-based assay after 3 hours at 37°C. The values (percent of cells) expressed as mean $\pm$ SD were derived from 6 separate measurements. Note the restoration of cell motility by the $\Delta N/\Delta C$ mutant β -catenin in the setting of inhibition of the signal transduction of the receptor level with stable expression of the dominant negative *FZD7* ΔC -C6 receptor mutant protein.

Figs. 7A-7C are a graph and Western blots illustrating *FZD7* expression in human HCC tumors and peritumorous liver parenchyma. Fig. 7A: a bar graph illustrating quantitative real-time RT-PCR assessment of *FZD7* mRNA levels in human HCC tumors (T) and the corresponding peritumorous liver parenchyma (pT), derived from Taiwan and South Africa. Non-parametric paired test, $*p < 0.0001$; paired *t*-test, $p = 0.0187$, when comparing levels in tumor to peritumoral areas. Fig. 7B: Western blot analysis of *FZD7* receptor protein expression in HCC tumors (T) and the corresponding peritumorous areas (pT), as well as in Huh7 and HepG2 human hepatoma cell lines. Fig. 7C: Western blot analysis of β -catenin protein accumulation in cytosolic (C) or nuclear (N) enriched fractions from two HCC tumors and their corresponding peritumoral areas compared to two normal liver samples. Both peritumoral area and tumor overexpress *FZD7* mRNA as shown by values listed below the Western blots and expressed as relative abundance of *FZD7* mRNA. Each tumor and peritumor region had a wildtype β -catenin exon-3 as assessed by PCR and sequencing.

Figs. 8A-8E illustrate exemplary *FZD7*, *FZD8*, Wnt 3, Wnt 8b and Wnt 11 human and mouse amino acid sequences, including putative binding motifs.

Figs. 9A-9J are pictures illustrating the histopathology of IRS-1/*c-myc*, X/*c-myc*, and SV40-Tag transgenic mouse livers. Figs. H&E, original magnification x100. Fig. 9A: Normal liver from a 8 week-old non-transgenic animal. Fig. 9B: Liver from a 24 week-old IRS-1/*c-myc* double transgenic showing large dysplastic cells (arrows). Fig. 9C: Peritumorous liver from a 36 week-old IRS-1/*c-myc* double transgenic showing large size foci of dysplastic cells. Fig. 9D: Well-differentiated HCC tumor of the trabecular type derived from a 36 week-old IRS-1/*c-myc* double transgenic mouse.

Fig. 9E: Liver from a 12 week-old X/c-*myc* double transgenic animal showing large dysplastic cells (arrows). Fig. 9F: Peritumorous liver from a 29 week-old X/c-*myc* double transgenic illustrating a large foci of dysplastic cells. Fig. 9G: Representative example of a well-differentiated HCC tumor of trabecular type derived from a 29 week-old X/c-*myc* double transgenic animal. Fig. 9H: Liver derived from a 5 week-old SV40-Tag single transgenic line showing proliferating hepatocytes with dysplastic features (arrows). Fig. 9I: Peritumorous liver from a 15 week-old SV40-Tag single transgenic showing diffuse microscopic infiltration by small HCC cells. Fig. 9J: Small cell HCC tumor derived from a 15 week-old SV40-Tag single transgenic animal.

Figs. 10A-10D are graphs illustrating steady state *FZD1*, *FZD4*, *FZD6*, *FZD7*, and *FZD8* mRNA expression levels as measured by RT-PCR in transgenic mice. Fig. 10A: c-*myc* Tg mice. Fig. 10B: IRS-1/c-*myc* Tg mice. Fig. 10C: X/c-*myc* Tg mice. Fig. 10D: SV40-Tag Tg mice. Black = HCC tumors, grey = dysplastic liver, and white = normal liver derived from non-transgenic littermates. Each value was normalized to the mean value of the corresponding non-transgenic littermates; *nb* = number of animals; *t*-Student test, (*) $p < 0.05$, (**) $p < 0.01$, (†) $p < 0.001$. All animals had a wild type β -catenin gene.

Fig. 11 is a series of line graphs illustrating the kinetics of *FZD7* mRNA expression during the multistep hepatocarcinogenesis in SV40-Tag, X/c-*myc*, and IRS-1/c-*myc* transgenic strains. Each value was normalized to the mean value found in the liver of the corresponding non-transgenic littermates; *nb* = number of animals; *t*-Student test, (*) $p < 0.05$, (**) $p < 0.01$, (†) $p < 0.001$.

Figs. 12A-12B are Western blots illustrating expression level of FZD7 receptor protein. Fig. 12A: FZD7 expression as revealed by a goat polyclonal antibody in whole cell extracts derived from non-transgenic normal (Lanes 1-2), and early dysplastic liver derived from 12 week-old X/c-*myc* double transgenics (Lanes 3-4), HCC tumors from 29 week-old X/c-*myc* double transgenics (Lanes 6 and 8), and the corresponding adjacent liver with multiple dysplastic foci (Lanes 5 and 7). Fig. 12B: the specificity of the 75 kDa band corresponding to the murine FZD7 observed on Western blot analysis with the goat polyclonal antibody, (A) was confirmed with a newly prepared rabbit polyclonal antibody targeting a 25-mer synthetic peptide specific of extracellular domain of FZD7 that reacts with both mouse and human derived FZD7 receptors. The human hepatoma cell lines Huh7 and HepG2 served as high and low positive human

controls as assessed by quantitative RT-PCR (21). In addition, murine HCC tumor derived from a SV40-Tag single transgenic and one 5-week-old dysplastic tumor-free liver served as high and low positive controls as assessed by quantitative RT-PCR.

Fig. 13 is a set of Western blots that provide a comparison between FZD7 receptor and β -catenin protein levels in protein extracts derived from four X/c-myc double transgenic animals with HCC tumors. The status of β -catenin gene was assessed by sequencing exon-2 of a PCR amplification product as described in below; wt = wild-type.

Figs. 14A-14B are bar graphs and Western blots illustrating the level of GSK3 β and phospho-GSK3 β during hepatocarcinogenesis. Fig. 14A: Western blot analysis of GSK3 β and phospho-GSK3 β level derived from: non-transgenic liver (black bar); early dysplastic liver of IRS-1/c-myc (8 and 24 weeks), X/c-myc (12 weeks) and SV40-Tag mice (5 weeks); tumors (T); and late dysplasia in the corresponding non-tumor (pT) of IRS-1/c-myc (36 weeks) and X/c-myc mice (30 weeks). Error bars represent the SEM of three independent experiments. Fig. 14B: Representative immunoblots with anti-GSK3 β and anti-phospho-GSK3 β antibodies.

Fig. 15 is a set of Western blots and a bar graph that provide an exemplary ratio between the level of total β -catenin and phospho β -catenin (Thr41/Ser45). The cytosolic fraction of a protein extract derived from X/c-myc double transgenics and SV40-Tag single transgenics was used for immunoblotting. The β -catenin gene status was wild-type as revealed by sequencing of exon-2. Note the increased ratio of total β -catenin /phospho β -catenin with evolution of HCC tumor in the two transgenic livers.

DETAILED DESCRIPTION

This invention is based, at least in part, on the discovery that particular Frizzled (FZD) proteins, e.g., FZD7 and 8, are associated with certain cancers, such as liver cancer. Accordingly, the present specification provides, *inter alia*, methods of using FZD proteins, genes, FZD-specific antibodies and probes in diagnosis and treatment of cancer and for screening test compounds for an ability to treat cancer. Also disclosed are compounds useful for treating cancer such as liver cancer.

I. Nucleic Acids, Proteins, Vectors, and Host Cells

The terms “Frizzled,” “FZD,” “Frizzled protein” and “Frizzled receptor” refer to a family of mammalian proteins related to the *Drosophila* Frizzled genes, which play a role in the development of tissue polarity. The Frizzled family comprises at least 10 mammalian genes. Exemplary human Frizzled receptors include Frizzled 1, Frizzled 2, Frizzled 3, Frizzled 4, Frizzled 5, Frizzled 6, Frizzled 7, Frizzled 8, Frizzled 9 and Frizzled 10. Frizzled receptors are involved in a dynamic model of transmembrane signal transduction analogous to G-protein-coupled receptors with amino-terminal ligand binding domains.

The terms “Wnt protein,” “Wnt ligand” and “Wnt” refer to a family of mammalian proteins related to the *Drosophila* segment polarity gene, wingless. In humans, the Wnt family of genes typically encode 38 to 43 kDa cysteine rich glycoproteins having hydrophobic signal sequence and a conserved asparagine-linked oligosaccharide consensus sequence (see e.g., Shimizu et al., *Cell Growth Differ* 8:1349-1358 (1997)). The Wnt family contains at least 19 mammalian members. Exemplary Wnt proteins include Wnt-1, Wnt-2, Wnt-2b (also known as Wnt-13), Wnt-3, Wnt-3A, Wnt-4, Wnt-5A, Wnt-5B, Wnt-6, Wnt-7A, Wnt-7B, Wnt-8A, Wnt-8B, Wnt-10A, Wnt-10B, Wnt-11, Wnt 14, Wnt 15, and Wnt 16.

In addition to Wnt ligands, a family of secreted Frizzled-related proteins (sFRPs) has been isolated. sFRPs appear to function as soluble endogenous modulators of Wnt signaling by competing with the membrane-spanning Frizzled receptors for the binding of secreted Wnt ligands. sFRPs can either antagonize Wnt function by binding the protein and blocking access to its cell surface signaling receptor, or they can enhance Wnt activity by facilitating the presentation of ligand to the Frizzled receptors.

The term “Wnt/FZD signaling pathway” refers to an intracellular signal transduction pathway that is initiated by an interaction between a Frizzled receptor, e.g., FZD7, and one or more of its ligands, e.g., a Wnt protein, e.g., Wnt 3, 8b or 11. Typically, a Wnt/FZD interaction involves binding of a Wnt protein, e.g., Wnt 3, 8b or 11, to a Frizzled receptor, e.g., FZD7, leading to activation of a signal transduction pathway. In some instances, activation of the Wnt/Frizzled signaling pathway will lead to induction of downstream-Wnt and/or FZD-inducible genes. A “downstream Wnt/FZD regulated gene product” is a protein or RNA that is regulated (e.g., up- or down-regulated) as a result of signaling by a Wnt/FZD signaling pathway.

The invention includes the use of certain FZD and Wnt nucleic acids. For example, the present invention includes the use of certain FZD7 and 8 nucleic acids, such as those that encode the amino acid sequences of the exemplary human and mouse FZD7 (SEQ ID NOs:1 and 3, respectively) and 8 (SEQ ID NO:4 and 6, respectively) receptors set forth in Figs. 8A to 8E. As another example, the invention includes the use of certain Wnt 3, 8b, and 11 nucleic acids, such as those that encode the amino acid sequences of the exemplary human and mouse Wnt 3 (SEQ ID NOs:7 and 13, respectively), 8b (SEQ ID NOs:14 and 20, respectively), and 11 (SEQ ID NOs:21 and 27, respectively) proteins set forth in Figs. 8A to 8E.

Also included within the present invention are the use of certain fragments of FZD and Wnt nucleic acids, e.g., a fragment of a nucleic acid sequence that encodes SEQ ID NOs:1, 3, 4, 6, 7, 13, 14, 20, 21, or 27. Fragments of FZD or Wnt nucleic acids encode at least one useful fragment of a FZD or Wnt polypeptide (e.g., a human or rodent polypeptide), respectively, such as a binding domain (e.g., a CRD domain) or other useful fragment. For example, a useful fragment of a FZD nucleic acid may encode a fragment of a FZD receptor having binding activity, e.g., a fragment corresponding to SEQ ID NO:3 or 5. As another example, a useful fragment of an Wnt nucleic acid may encode a fragment of a Wnt polypeptide having binding activity, e.g., a fragment corresponding to any one or more of SEQ ID NOs:8 to 12, 15 to 19 and 22 to 26.

FZD and Wnt nucleic acids described herein include both RNA and DNA, including genomic DNA and synthetic (e.g., chemically synthesized) DNA. Nucleic acids can be double-stranded or single-stranded. Where single-stranded, the nucleic acid can be a sense strand or an antisense strand. Nucleic acids can be synthesized using oligonucleotide analogs or derivatives (e.g., inosine or phosphorothioate nucleotides). Such oligonucleotides can be used, for example, to prepare nucleic acids that have altered base-pairing abilities or increased resistance to nucleases.

An "isolated nucleic acid" is a nucleic acid the structure of which is not identical to that of any naturally occurring nucleic acid or to that of any spanning more than three separate genes. The term therefore covers, for example, (a) a DNA which has the sequence of part of a naturally occurring genomic DNA molecule but is not flanked by both of the coding sequences that flank that part of the molecule in the genome of the organism in which it naturally occurs; (b) a nucleic acid incorporated

into a vector or into the genomic DNA of a prokaryote or eukaryote in a manner such that the resulting molecule is not identical to any naturally occurring vector or genomic DNA; (c) a separate molecule such as a cDNA, a genomic fragment, a fragment produced by polymerase chain reaction (PCR), or a restriction fragment; and (d) a recombinant nucleotide sequence that is part of a hybrid gene, i.e., a gene encoding a fusion protein. Specifically excluded from this definition are nucleic acids present in mixtures of (i) DNA molecules, (ii) transfected cells; and (iii) cell clones, e.g., as these occur in a DNA library such as a cDNA or genomic DNA library.

In some embodiments, the invention includes the use of nucleic acid sequences that are substantially homologous to a FZD or Wnt nucleic acid. A nucleic acid sequence that is "substantially homologous" to a FZD or Wnt nucleic acid is at least 75% homologous to FZD or Wnt nucleic acid sequences that encode any one of SEQ ID NOs:1 to 27. For example, substantially homologous nucleic acid sequences can be at least about 80%, 85%, 90%, 95%, 98%, or at least about 99% homologous to sequences that encode SEQ ID NOs:1 to 27. For purposes of comparison of nucleic acids, the length of the reference nucleic acid sequence will be at least 50 nucleotides, but can be longer, e.g., at least 60 nucleotides, or more nucleotides.

As used herein, "percent homology" of two amino acid sequences or two nucleic acid sequences is determined using the algorithm of Karlin and Altschul (1990) *Proc. Nat'l Acad. Sci. USA* 87:2264-2268, modified as in Karlin and Altschul (1993) *Proc. Nat'l Acad. Sci. USA* 90:5873-5877. Such an algorithm is incorporated into the NBLAST and XBLAST programs of Altschul, et al. (1990); *J. Mol. Biol.* 215:403-410. BLAST nucleotide searches are performed with the NBLAST program, score = 100, wordlength = 12 to obtain nucleotide sequences homologous to FZD or Wnt nucleic acid molecules used in the invention. BLAST protein searches are performed with the XBLAST program, score = 50, wordlength = 3 to obtain amino acid sequences homologous to a reference polypeptide. To obtain gapped alignments for comparison purposes, Gapped BLAST is utilized as described in Altschul et al., (1997) *Nucleic Acids Res.* 25:3389-3402. When utilizing BLAST and Gapped BLAST programs, the default parameters of the respective programs (e.g., XBLAST and NBLAST) are used. See the World Wide Web at address ncbi.nlm.nih.gov.

The invention also includes the use of nucleic acids that hybridize under stringent hybridization conditions (as defined herein) to all or a portion of nucleotide

sequences that encode any of SEQ ID NOs:1 to 27, or to a complement of such nucleic acid sequences. The hybridizing portion of the hybridizing nucleic acids is typically at least 15 (e.g., 20, 25, 30, or 50) nucleotides in length. The hybridizing portion of the hybridizing nucleic acid is at least about 75% (e.g., at least 80%, 90%, 95% or 98%) identical to the sequence of a portion or all of a nucleic acid encoding an FZD or Wnt polypeptide, or to its complement. Hybridizing nucleic acids of the type described herein can be used, for example, as a cloning probe, a primer (e.g., a PCR primer), or a diagnostic probe. Hybridization of the oligonucleotide probe to a nucleic acid sample typically is performed under stringent conditions. Nucleic acid duplex or hybrid stability is expressed as the melting temperature or T_m , which is the temperature at which a probe dissociates from a target DNA. This melting temperature is used to define the required stringency conditions. If sequences are to be identified that are related and substantially identical to the probe, rather than identical, then it is useful to first establish the lowest temperature at which only homologous hybridization occurs with a particular concentration of salt (e.g., SSC or SSPE).

Then, assuming that 1% mismatching results in a 1°C decrease in the T_m , the temperature of the final wash in the hybridization reaction is reduced accordingly (for example, if sequences having > 95% identity with the probe are sought, the final wash temperature is decreased by 5°C). In practice, the change in T_m can be between 0.5°C and 1.5°C per 1% mismatch. Stringent conditions involve hybridizing at 68°C in 5x SSC/5x Denhardt's solution/1.0% SDS, and washing in 0.2x SSC/0.1% SDS at room temperature. Moderately stringent conditions include washing in 3 x SSC at 42°C. The parameters of salt concentration and temperature can be varied to achieve the optimal level of identity between the probe and the target nucleic acid. Additional guidance regarding such conditions is readily available in the art, for example, by Sambrook et al., 1989, *Molecular Cloning, A Laboratory Manual*, Cold Spring Harbor Press, N.Y.; and Ausubel et al. (eds.), 1995, *Current Protocols in Molecular Biology*, (John Wiley & Sons, N.Y.) at Unit 2.10.

Nucleic acids that hybridize to nucleotide sequence that encode any of SEQ ID NOs:1 to 27 are considered "antisense oligonucleotides."

Also included in the invention are genetic constructs (e.g., vectors and plasmids) that include a FZD and/or Wnt nucleic acid described herein, operably linked to a transcription and/or translation sequence to enable expression, e.g., expression

vectors. A selected nucleic acid, e.g., a DNA molecule encoding a FZD or Wnt polypeptide, is "operably linked" to another nucleic acid molecule, e.g., a promoter, when it is positioned in such a way that the other molecule can direct transcription and/or translation of the selected nucleic acid. For example, the selected nucleic acid can be positioned adjacent to the other nucleic acid molecule.

Also included in the invention are various engineered cells which contain a FZD and/or Wnt nucleic acid described herein. For example, the invention includes transformed host cells, i.e., cells into which (or into an ancestor of which) has been introduced, by means of recombinant DNA techniques, a nucleic acid encoding a FZD and/or Wnt polypeptide. Both prokaryotic and eukaryotic cells are included, e.g., mammalian cells (e.g., liver cells), fungi, and bacteria (such as *Escherichia coli*), and the like. An engineered cell exemplary of the type included in the invention is a liver cell that overexpresses a FZD7 transgene.

A cell that "overexpresses FZD" is a cancer cell and/or transgenic cell in which expression of a particular FZD protein, such as FZD7 and/or 8, is at least about 1.5 times, e.g., at least about 2, 3, 4 or 5 times, the level of expression in a non-cancer cell or non-transgenic cell, respectively, from the same tissue type. In some embodiments, FZD expression in a cell can be compared to expression in a non-cancer or non-transgenic cell of a different tissue-type or a panel of non-cancer or non-transgenic cells of a different tissue type. In addition, expression of one type of FZD protein (e.g., FZD7) can be compared to other FZD proteins in the same cell. Methods for determining the level of expression of a particular gene are well known in the art. Such methods include, but are not limited to, RT-PCR, real time PCR and use of antibodies against the gene products.

The use of certain FZD and Wnt polypeptides are also included within the present invention. Examples of FZD polypeptides used in the present invention are human and mouse FZD polypeptides, such as those shown in SEQ ID NOs:1 and 3, respectively, and SEQ ID NOs:4 and 6, respectively. Examples of Wnt polypeptides used in the present invention are human and mouse Wnt 3, 8b and 11 polypeptides, such as those shown in SEQ ID NOs:7, 13, 14, 20, 21 and 27. Also included used in the present invention are certain fragments of FZD and Wnt polypeptides, e.g., fragments of SEQ ID NOs:1, 3, 4, 6, 7, 13, 14, 20, 21 and 27. Fragments of FZD and Wnt polypeptides may include at least one binding domain, or other useful portion of a

full-length FZD and Wnt polypeptide. For example, useful fragments of FZD and Wnt polypeptides include, but are not limited to, fragments having binding activity (e.g., SEQ ID NOs: 2, 5, 8 to 12, 15 to 19, and 22 to 26).

The terms "protein" and "polypeptide" both refer to any chain of amino acids, regardless of length or post-translational modification (e.g., glycosylation or phosphorylation). Thus, the terms "Frizzled protein," "Wnt protein," "Frizzled polypeptide," and "Wnt polypeptide" include full-length naturally occurring isolated proteins, as well as recombinantly or synthetically produced polypeptides that correspond to the full-length naturally occurring proteins, or to a fragment of the full-length naturally occurring or synthetic polypeptide.

As discussed above, the terms "Frizzled polypeptide," and "Wnt polypeptide" include biologically active fragments of naturally occurring or synthetic FZD and Wnt polypeptides, respectively. Fragments of a protein can be produced by any of a variety of methods known to those skilled in the art, e.g., recombinantly, by proteolytic digestion, or by chemical synthesis. Internal or terminal fragments of a polypeptide can be generated by removing one or more nucleotides from one end (for a terminal fragment) or both ends (for an internal fragment) of a nucleic acid that encodes the polypeptide. Expression of such mutagenized DNA can produce polypeptide fragments. Digestion with "end-nibbling" endonucleases can generate DNAs that encode an array of fragments. DNAs that encode fragments of a protein can also be generated, e.g., by random shearing, restriction digestion, chemical synthesis of oligonucleotides, amplification of DNA using the polymerase chain reaction, or a combination of the above-discussed methods. Fragments can also be chemically synthesized using techniques known in the art, e.g., conventional Merrifield solid phase Fmoc or t-Boc chemistry.

A purified or isolated compound is a composition that is at least 60% by weight the compound of interest, e.g., a FZD polypeptide, Wnt polypeptide, or antibody. For example, the preparation can be at least 75% (e.g., at least 90%, 95%, or even 99%) by weight the compound of interest. Purity can be measured by any appropriate method known in the art, e.g., column chromatography, polyacrylamide gel electrophoresis, or HPLC analysis.

In certain embodiments, FZD and Wnt polypeptides include sequences substantially identical to all or portions of a naturally occurring FZD and Wnt

polypeptides. Polypeptides “substantially homologous” to the FZD and Wnt polypeptide sequences described herein have an amino acid sequence that is at least 65% (e.g., at least 75%, 80%, 85%, 90%, 95% or 99%, e.g., 100%), homologous to an amino acid sequence represented by SEQ ID NOs:1 to 27 (measured as described
5 herein). For purposes of comparison, the length of the reference FZD and Wnt polypeptide sequence can be at least 16 amino acids, e.g., at least 20 or 25 amino acids.

A “conservative amino acid substitution” is one in which the amino acid residue is replaced with an amino acid residue having a similar side chain. Families of amino acid residues having similar side chains have been defined in the art. These families
10 include amino acids with basic side chains (e.g., lysine, arginine, histidine), acidic side chains (e.g., aspartic acid, glutamic acid), uncharged polar side chains (e.g., glycine, asparagine, glutamine, serine, threonine, tyrosine, cysteine), nonpolar side chains (e.g., alanine, valine, leucine, isoleucine, proline, phenylalanine, methionine, tryptophan), beta-branched side chains (e.g., threonine, valine, isoleucine) and aromatic side chains
15 (e.g., tyrosine, phenylalanine, tryptophan, histidine).

The invention also includes the use of fusion proteins (and nucleic acids that encode such fusion proteins) in which a portion of a FZD (e.g., FZD7 and/or 8) or Wnt (e.g., Wnt 3, 8b and/or 11) polypeptide is fused to an unrelated polypeptide (e.g., a marker polypeptide or a fusion partner) to create a fusion protein. For example, the
20 polypeptide can be fused to a hexa-histidine tag or a FLAG tag to facilitate purification of bacterially expressed polypeptides or to a hemagglutinin tag or a FLAG tag to facilitate purification of polypeptides expressed in eukaryotic cells. The invention also includes, for example, the use of isolated polypeptides (and the nucleic acids that encode these polypeptides) that include a first portion and a second portion, wherein the
25 first portion includes, e.g., a FZD or Wnt polypeptide, and the second portion includes an unrelated polypeptide, e.g., an immunoglobulin constant (Fc) region or a detectable marker.

The fusion partner can be, for example, a polypeptide that facilitates secretion, e.g., a secretory sequence. Such a fused polypeptide is typically referred to as a
30 preprotein. The secretory sequence can be cleaved by the host cell to form the mature protein. Also within the invention are nucleic acids that encode a FZD and/or Wnt polypeptide fused to a polypeptide sequence to produce an inactive preprotein.

Preproteins can be converted into the active form of the protein by removal of the inactivating sequence.

II. Methods for Detecting Cancer

5 Without being bound by theory, it appears that various FZD proteins, e.g., FZD7 and 8, are important in cancer, e.g., liver cancer. In particular, hepatocytes appear to overexpress FZD7 early during the process of transformation, e.g., prior to the development of HCC. Similarly, such cells often underexpress FZD8.

10 Accordingly, the present invention provides methods of detecting cancer cells, facilitating the diagnosis of the presence and severity (e.g., tumor grade, tumor burden, and the like) of cancer in a patient, facilitating a determination of the prognosis of a patient and assessing the responsiveness of the patient to therapy (e.g., by providing a measure of therapeutic effect through, for example, assessing tumor burden during or following a chemotherapeutic regimen).

15 Detection can be based on detection of a polynucleotide (e.g., a FZD7 and/or 8 polynucleotide) that is differentially expressed in a cancer cell (e.g., as compared to a non-cancer cell) and/or detection of a polypeptide (e.g., a FZD7 and/or 8 polypeptide) encoded by a polynucleotide that is differentially expressed in a cancer cell. The detection methods of the invention can be conducted *in vitro* or *in vivo*, on a biological sample, e.g., isolated cells and/or whole tissues.

20 A "biological sample" as used herein is a sample of biological tissue or fluid that contains nucleic acids or polypeptides, e.g., a FZD7 protein, polynucleotide or transcript. Such samples include, but are not limited to, tissue obtained from, e.g., liver, lung, lymph nodes, colon, stomach, pancreas, bile duct, small bowel and/or esophagus. Biological samples may also include sections of tissues such as biopsy and autopsy samples, frozen sections taken for histologic purposes, blood, plasma, serum, sputum, stool, tears, mucus, bile, saliva, lymph, hair, skin, etc. Biological samples also include explants and primary and/or transformed cell cultures derived from patient tissues. A biological sample is typically obtained from a eukaryotic organism, e.g., a
30 primate such as a chimpanzee or human; cow; horse; goat; sheep; dog; cat; a rodent, e.g., guinea pig, rat or mouse; rabbit; bird; reptile; or fish. A sample is usually provided by removing a sample of cells from an animal, but can also be accomplished by providing previously isolated cells (e.g., isolated by another person, at another time

and/or for another purpose), or by performing the methods of the invention *in vivo*. Archival tissues, having treatment or outcome history, can be used.

In some embodiments, methods are provided for detecting a cancer cell by detecting expression in the cell of a transcript (e.g., a FZD7 and/or 8 transcript) that is
5 differentially expressed in a cancer cell. Any of a variety of known methods can be used for detection including but not limited to, detection of a transcript by hybridization of mRNA with an appropriate hybridization probe; detection of a transcript by a polymerase chain reaction using specific oligonucleotide primers; and *in situ* hybridization using an appropriate hybridization probe. The methods can be used to
10 detect and/or measure mRNA levels of a gene that is differentially expressed in a cancer cell. In some embodiments, the methods comprise: a) contacting a sample with a polynucleotide that corresponds to a differentially expressed gene described herein under conditions that allow hybridization; and b) detecting hybridization, if any.

Detection of differential hybridization, when compared to a suitable control, is
15 an indication of the presence in the sample of a polynucleotide that is differentially expressed in a cancer cell. Appropriate controls include, for example, a sample that is not a cancer cell, a sample that is known not to contain a polynucleotide that is differentially expressed in a cancer cell, and use of a labeled polynucleotide of the same “sense” as the polynucleotide that is differentially expressed in the cancer cell.
20 Conditions that allow hybridization are known in the art and have been described in more detail above. Detection can also be accomplished by any known method, including, but not limited to, *in situ* hybridization, PCR (polymerase chain reaction) and/or RT-PCR (reverse transcription-PCR), or combinations of known techniques. A variety of labels and labeling methods for polynucleotides are known in the art and can
25 be used in the assay methods of the invention. Specificity of hybridization can be determined by comparison to appropriate controls.

Polynucleotides generally comprising at least 10 nt, at least 12 nt or at least 15 contiguous nucleotides of a polynucleotide described herein, such as those having the sequence as depicted herein, can be used for a variety of purposes, such as probes or
30 PCR primers for detection and/or measurement of transcription levels of a polynucleotide that is differentially expressed in a cancer cell. As will be appreciated by the skilled artisan, the probe can be detectably labeled and contacted with, for example, an array comprising immobilized polynucleotides obtained from a test sample

(e.g., mRNA). Alternatively, the probe can be immobilized on an array and the test sample detectably labeled. The use of these and other variations of the methods of the invention are well within the skill in the art and are within the scope of the invention.

5 Nucleotide probes can be used to detect expression of a gene corresponding to the provided polynucleotide. In Northern blots, mRNA is separated electrophoretically and contacted with a probe. A probe is detected as hybridizing to an mRNA species of a particular size. The amount of hybridization can be quantified to determine relative amounts of expression. Probes can be used for *in situ* hybridization to cells to detect expression. Probes can also be used *in vivo* for diagnostic detection of hybridizing
10 sequences. Probes can be labeled with a radioactive isotope or other types of detectable labels, e.g., chromophores, fluorophores and/or enzymes. Other examples of nucleotide hybridization assays are described in WO92/02526 and U.S. Pat. No. 5,124,246.

PCR is another means for detecting small amounts of target nucleic acids (see, e.g., Mullis et al., Meth. Enzymol. (1987) 155:335; U.S. Pat. No. 4,683,195; and U.S.
15 Pat. No. 4,683,202). Two primer oligonucleotides that hybridize with the target nucleic acids can be used to prime the reaction. The primers can be composed of sequence within or 3' and 5' to the polynucleotides described herein. After amplification of the target by standard PCR methods, the amplified target nucleic acids can be detected by methods known in the art, e.g., Southern blot. mRNA or cDNA can also be detected by
20 traditional blotting techniques (e.g., Southern blot, Northern blot, etc.) described in Sambrook et al., "Molecular Cloning: A Laboratory Manual" (New York, Cold Spring Harbor Laboratory, 1989) (e.g., without PCR amplification). In general, mRNA or cDNA generated from mRNA using a polymerase enzyme can be purified and separated using gel electrophoresis, and transferred to a solid support, such as
25 nitrocellulose. The solid support can be exposed to a labeled probe and washed to remove any unhybridized probe. Duplexes containing the labeled probe can then be detected.

Methods using PCR amplification can be performed on the DNA from one or more cells. The use of the polymerase chain reaction is described in Saiki et al. (1985)
30 Science 239:487, and a review of techniques may be found in Sambrook et al., "Molecular Cloning: A Laboratory Manual" (New York, Cold Spring Harbor Laboratory, 1989; pp.14.2-14.33). A detectable label may be included in the amplification reaction. Suitable detectable labels include fluorochromes, (e.g.

fluorescein isothiocyanate (FITC), rhodamine, Texas Red, phycoerythrin, allophycocyanin, 6-carboxyfluorescein (6-FAM), 2',7'-dimethoxy-4',5'-dichloro-6-carboxyfluorescein, 6-carboxy-X-rhodamine (ROX), 6-carboxy- 2',4,4',5',7,7' - hexachlorofluorescein (HEX), 5-carboxyfluorescein (5-FAM) or N,N,N',N'-tetramethyl-6-carboxyrhodamine (TAMRA)), radioactive labels, (e.g., ^{32}P , ^{35}S , ^3H , etc.), and the like. The label may be a two stage system, where the polynucleotide is conjugated to biotin, haptens, etc. having a high affinity binding partner, e.g. avidin, specific antibodies, etc., where the binding partner is conjugated to a detectable label. The label may be conjugated to one or both of the primers. Alternatively, the pool of nucleotides used in the amplification is labeled, so as to incorporate the label into the amplification product.

In one embodiment, expression level is assessed by using real time PCR. RNA is isolated from a sample of interest. PCR primers are designed to amplify the specific gene of interest. PCR product accumulation is measured using a dual-labeled fluorescent oligonucleotide probe. The probe is labeled with two different fluorescent dyes, the 5' terminus reporter dye and the 3' terminus quenching dye. The oligonucleotide probe is selected to be homologous to an internal target sequence present in the PCR amplicon. When the probe is intact, energy transfer occurs between the two fluorophores, and the fluorescent emission is quenched. During the extension phase of PCR, the probe is cleaved by 5' nuclease activity of Taq polymerase. Therefore, the reporter is no longer in proximity to the quencher, and the increase in emission intensity is measured. An exemplary method for detecting FZD expression using real time PCR is provided in the Examples section, below. The primers can also be used in other methods, for example RT-PCR. This assay provides a quantitative measure of nucleic acid.

In other embodiments, methods are provided for detecting a cancer cell by detecting expression of a protein (e.g., a FZD7 and/or 8 protein) that is differentially expressed by the cell. Any of a variety of known methods can be used for detection, including but not limited to methods that employ binding compounds, e.g., antibodies, e.g., as is useful in ELISA and/or Western blotting methods. Such an antibodies can be polyclonal or monoclonal, or antigen binding fragment thereof, and can be labeled with a detectable marker (e.g., fluorophore, chromophore or isotope, etc). Where appropriate, the compound can be attached to a solid support such as a bead, plate,

filter, resin, etc. Determination of formation of the compound/target complex can be effected by contacting the complex with a further compound (e.g., a secondary antibody) that specifically binds to the first compound (or complex). Like the first compound, the further compound can be attached to a solid support and/or can be
5 labeled with a detectable marker.

The materials needed to perform the detection methods described herein can be provided as part of a kit. Thus, the invention further provides kits for detecting the presence and/or a level of a polynucleotide that is differentially expressed in a cancer cell (e.g., by detection of an mRNA encoded by the differentially expressed gene of
10 interest), and/or a polypeptide encoded thereby, in a biological sample. Procedures using these kits can be performed by clinical laboratories, experimental laboratories, medical practitioners or private individuals. The kits of the invention for detecting a polypeptide encoded by a polynucleotide that is differentially expressed in a cancer cell may comprise a moiety, such as an antibody, that specifically binds the polypeptide.

The kits of the invention used for detecting a polynucleotide that is differentially
15 expressed in a cancer cell may comprise a moiety that specifically hybridizes to such a polynucleotide. The kit may optionally provide additional components that are useful in the procedure including, e.g., buffers, developing reagents, labels, reacting surfaces, means for detection, control samples, standards, instructions, and interpretive
20 information.

The present invention further relates to methods of detecting/diagnosing a neoplastic or preneoplastic condition in a mammal (for example, a human).

"Diagnosis" as used herein generally includes determination of a patient's susceptibility to a disease or disorder, determination as to whether a subject is presently affected by a
25 disease or disorder, prognosis of a subject affected by a disease or disorder (e.g., identification of pre-metastatic or metastatic cancerous states, stages of cancer, or responsiveness of cancer to therapy), and therametrics (e.g., monitoring a subject's condition to provide information as to the effect or efficacy of therapy).

One exemplary detection/diagnostic method includes: (a) obtaining from a
30 mammal (e.g., a human) a biological sample (e.g., liver tissue), (b) detecting in the sample the presence of a FZD7 and/or 8 gene product (e.g., protein or mRNA), and (c) comparing the amount of FZD7 and/or 8 gene product present with that in a control sample. In accordance with this method, the presence in the sample of elevated levels

of FZD7 gene product and/or reduced levels of FZD8 gene product indicates that the subject has a neoplastic or preneoplastic condition, e.g., liver cancer or a risk for developing liver cancer.

The identification of elevated levels of FZD7 protein and/or reduced levels of FZD8 protein in accordance with the present invention makes possible the identification of patients that are likely to benefit from specialized therapy. For example, a biological sample from a post primary therapy subject (e.g., subject having undergone surgery) can be screened for the presence of elevated levels of the protein, determined by studies of normal populations, being indicative of residual tumor tissue. Similarly, tissue surrounding the cut site of a surgically removed tumor (e.g., peritumorous tissue) can be examined (e.g., by immunofluorescence), the presence of elevated levels of FZD7 or reduced levels of FZD8 (relative to the surrounding tissue) being indicative of potential development of the disease in this tissue or incomplete removal of the tumor. The ability to identify such patients makes it possible to tailor therapy to the needs of the particular patient. Subjects undergoing non-surgical therapy, e.g., chemotherapy or radiation therapy, can also be monitored, the presence in samples from such subjects of elevated levels of FZD7 or reduced levels of FZD8 being indicative of the need for continued treatment. Skilled practitioners will also appreciate that staging of cancer (e.g., liver cancer) for purposes of optimizing treatment regimens can be performed using the methods described herein.

III. Methods for Identifying Compounds Capable of Treating Cancer

The invention provides methods for screening test compounds for an ability to treat cancer, e.g., liver cancer. A "test compound" as described herein is any compound that can be screened using the methods described herein. For example, a test compound can be, e.g., a small organic or inorganic molecule (M.W. less than 1,000 Da). Alternatively or in addition, the test compound can be a polypeptide (e.g., a polypeptide having a random or predetermined amino acid sequence or a naturally-occurring or synthetic polypeptide) or a nucleic acid, such as a DNA or RNA molecule. A test compound can be naturally occurring (e.g., an herb or a natural product), or synthetic, or can include both natural and synthetic components. A test compound can have a formula weight of less than about 10,000 grams per mole, less than 5,000 grams per mole, less than 1,000 grams per mole, or less than about 500 grams per mole. The

test compound can be, for example, any organic or inorganic compound (e.g., heteroorganic or organometallic compound), an amino acid, amino acid analog, polypeptide, peptidomimetic (e.g., peptoid), oligopeptide (e.g., from about 5 to about 25 amino acids in length, preferably from about 10 to 20 or 12 to 18 amino acids in length, preferably 12, 15, or 18 amino acids in length), nucleotide, nucleotide analog, polynucleotide, polynucleotide analog, ribonucleic acid, deoxyribonucleic acid, antisense oligonucleotide, ribozyme, saccharide, lipid (e.g., a sphingolipid), and/or a fatty acid, or any combination thereof.

The terms “antagonist” or “inhibitor” of Wnt/FZD signaling (e.g., Wnt/FZD7 signaling) refer to compounds that, e.g., bind to Wnt proteins (e.g., Wnt 3, 8, and/or 11) and/or FZD receptors (e.g., FZD7) and/or partially or totally block or inhibit Wnt/FZD signaling (e.g., Wnt/FZD7 signaling) as measured in known assays for Wnt/FZD signaling (e.g., measurement of β -catenin levels, oncogene expression controlled by Tcf and Lef transcription factors or other downstream Wnt/Frizzled regulated gene products). Inhibitors include, e.g., antibodies directed against Wnt or FZD proteins, modified versions of Wnt or FZD proteins, naturally occurring and synthetic ligands, antagonists, agonists, antibodies, small chemical molecules, and the like. Assays for detecting inhibitors or antagonists are described in more detail below.

Libraries of Test Compounds

In certain embodiments, screens of the present invention utilize libraries of test compounds. A “library” is a collection of compounds (e.g., as a mixture or as physically separated individual compounds) synthesized from various combinations of one or more starting components. At least some of the compounds must differ from at least some of the other compounds in the library. A library can include, e.g., 5, 10, 50, 100, 1000, or even 10,000, 50,000, or 100,000, or more different compounds (i.e., not simply multiple copies of the same compounds, although some compounds in the library may be duplicated or represented more than once). Each of the different compounds will be present in an amount such that its presence can be determined by some means, e.g., can be isolated, analyzed, and/or detected with a receptor or suitable probe. The actual quantity of each different compound needed so that its presence can be determined will vary due to the actual procedures used and may change as the technologies for isolation, detection, and analysis advance. When the compounds are

present in a mixture in substantially equimolar amounts, for example, an amount of 100 picomoles of each compound can often be detected. Libraries can include both libraries of individual compounds (e.g., present substantially as a single type of compound-per-well, made via parallel synthesis or the pool and split pool method) and mixtures
5 containing substantially equimolar amounts of each desired compound (i.e., wherein no single compound dominates). Either library format can allow identification of an active compound discovered in an assay.

Test compounds can be screened individually or in parallel. An example of parallel screening is a high throughput drug screen of large libraries of chemicals. Such
10 libraries of candidate compounds can be generated or purchased, e.g., from Chembridge Corp., San Diego, CA. Alternatively, prior experimentation and anecdotal evidence can suggest a class or category of compounds of enhanced potential. A library can be designed and synthesized to cover such a class of chemicals.

The synthesis of combinatorial libraries is well known in the art and has been
15 reviewed (see, e.g., E.M. Gordon *et al.*, *J. Med. Chem.* (1994) 37:1385-1401 ; DeWitt, S. H.; Czarnik, A. W. *Acc. Chem. Res.* (1996) 29:114; Armstrong, R. W.; Combs, A. P.; Tempest, P. A.; Brown, S. D.; Keating, T. A. *Acc. Chem. Res.* (1996) 29:123; Ellman, J. A. *Acc. Chem. Res.* (1996) 29:132; Gordon, E. M.; Gallop, M. A.; Patel, D. V. *Acc. Chem. Res.* (1996) 29:144; Lowe, G. *Chem. Soc. Rev.* (1995) 309, Blondelle *et al. Trends Anal. Chem.* (1995) 14:83; Chen *et al. J. Am. Chem. Soc.* (1994) 116:2661;
20 U.S. Patents 5,359,115, 5,362,899, and 5,288,514; PCT Publication Nos. WO92/10092, WO93/09668, WO91/07087, WO93/20242, WO94/08051).

Libraries of compounds can be prepared according to a variety of methods, some of which are known in the art. For example, a "split-pool" strategy can be
25 implemented in the following way: beads of a functionalized polymeric support are placed in a plurality of reaction vessels; a variety of polymeric supports suitable for solid-phase peptide synthesis are known, and some are commercially available (for examples, see, e.g., M. Bodansky "Principles of Peptide Synthesis", 2nd edition, Springer-Verlag, Berlin (1993)). To each aliquot of beads is added a solution of a
30 different activated amino acid, and the reactions are allowed to proceed to yield a plurality of immobilized amino acids, one in each reaction vessel. The aliquots of derivatized beads are then washed, "pooled" (i.e., recombined), and the pool of beads is again divided, with each aliquot being placed in a separate reaction vessel. Another

activated amino acid is then added to each aliquot of beads. The cycle of synthesis is repeated until a desired peptide length is obtained. The amino acid residues added at each synthesis cycle can be randomly selected; alternatively, amino acids can be selected to provide a "biased" library, e.g., a library in which certain portions of the inhibitor are selected non-randomly, e.g., to provide an inhibitor having known structural similarity or homology to a known peptide capable of interacting with an antibody, e.g., the an anti-idiotypic antibody antigen binding site. It will be appreciated that a wide variety of peptidic, peptidomimetic, or non-peptidic compounds can be readily generated in this way.

The "split-pool" strategy can result in a library of peptides, e.g., modulators, which can be used to prepare a library of test compounds of the invention. In another illustrative synthesis, a "diversomer library" is created by the method of Hobbs DeWitt *et al.* (*Proc. Natl. Acad. Sci. U.S.A.* 90:6909 (1993)). Other synthesis methods, including the "tea-bag" technique of Houghten (see, e.g., Houghten *et al.*, *Nature* 354:84-86 (1991)) can also be used to synthesize libraries of compounds according to the subject invention.

Libraries of compounds can be screened to determine whether any members of the library have a desired activity, and, if so, to identify the active species. Methods of screening combinatorial libraries have been described (see, e.g., Gordon *et al.*, *J Med. Chem.*, *supra*). Soluble compound libraries can be screened by affinity chromatography with an appropriate receptor to isolate ligands for the receptor, followed by identification of the isolated ligands by conventional techniques (e.g., mass spectrometry, NMR, and the like). Immobilized compounds can be screened by contacting the compounds with a soluble receptor; preferably, the soluble receptor is conjugated to a label (e.g., fluorophores, colorimetric enzymes, radioisotopes, luminescent compounds, and the like) that can be detected to indicate ligand binding. Alternatively, immobilized compounds can be selectively released and allowed to diffuse through a membrane to interact with a receptor. Exemplary assays useful for screening libraries of test compounds are described above.

Screening Methods

The invention provides methods for identifying compounds capable of treating cancer, e.g., liver cancer. Although applicants do not intend to be bound by any

particular theory as to the biological mechanism involved, such compounds are thought to modulate specifically (1) Wnt/FZD signaling (e.g., by binding to FZD7, Wnt 3, Wnt 8b and/or Wnt 11 polypeptides and/or reducing (e.g., preventing) Wnt/FZD-mediated transcription) and/or (2) expression of FZD7 and/or FZD8.

5 In certain aspects of the present invention, screening for such compounds is accomplished by (i) identifying from a group of test compounds those that bind to a FZD7, Wnt 3, Wnt 8b and/or Wnt 11 polypeptide, modulate an interaction between FZD7 and its ligand (e.g., Wnt 3, Wnt 8b and/or Wnt 11) and/or modulate (i.e., increase or decrease) transcription and/or translation of FZD7 and/or FZD8; and, optionally,
10 (ii) further testing such compounds for their ability to modulate Wnt/FZD signaling, reduce cancer cell motility, reduce β -catenin accumulation in cancer cells and/or to treat cancer *in vitro* or *in vivo*. Test compounds that bind to FZD7, Wnt 3, Wnt 8b and/or Wnt 11 polypeptides, modulate an interaction between FZD7 and its ligand (e.g., Wnt 3, Wnt 8b and/or Wnt 11), or modulate transcription and/or translation of FZD7
15 and/or FZD8, are referred to herein as "candidate anti-cancer agents." Candidate anti-cancer agents further tested and found to be capable of modulating *in vitro* or *in vivo* Wnt/FZD signaling, reducing cancer cell motility, reduce β -catenin accumulation in cancer cells, and/or treating cancer are considered "anti-cancer agents." In the screening methods of the present invention, candidate anti-cancer agents can be, but do
20 not necessarily have to be, tested to determine whether they are anti-cancer agents. Assays of the present invention may be carried out in biological samples, whole cell preparations and/or *ex vivo* cell-free systems:

In one aspect, the invention includes methods for screening test compounds to identify compounds that bind to FZD polypeptides, e.g., FZD7 polypeptides, and/or to
25 Wnt polypeptides, e.g., Wnt 3, 8b and/or 11 polypeptides. Binding of a test compound to a FZD or Wnt polypeptide can be detected, for example, *in vitro* by reversibly or irreversibly immobilizing the test compound(s) or the Wnt or FZD polypeptide on a substrate, e.g., the surface of a well of a 96-well polystyrene microtitre plate. Methods for immobilizing polypeptides and other small molecules are well known in the art.
30 For example, microtitre plates can be coated with a FZD or Wnt polypeptide by adding the polypeptide in a solution (typically, at a concentration of 0.05 to 1 mg/ml in a volume of 1-100 μ l) to each well, and incubating the plates at room temperature to 37°C for a given amount of time, e.g., for 0.1 to 36 hours. Polypeptides not bound to

the plate can be removed by shaking excess solution from the plate, and then washing the plate (once or repeatedly) with water or a buffer. Typically, the polypeptide is in water or a buffer. The plate can then be washed with a buffer that lacks the bound polypeptide. To block the free protein-binding sites on the plates, plates can be blocked
5 with a protein that is unrelated to the bound polypeptide. For example, 300 μ l of bovine serum albumin (BSA) at a concentration of 2 mg/ml in Tris-HCl can be used. Suitable substrates include those substrates that contain a defined cross-linking chemistry (e.g., plastic substrates, such as polystyrene, styrene, or polypropylene substrates from Corning Costar Corp. (Cambridge, MA), for example). If desired, a
10 particle, e.g., beaded agarose or beaded sepharose, can be used as the substrate. Test compounds can then be added to the coated plate and allowed to bind to the FZD or Wnt polypeptide (e.g., at 37°C for 0.5 - 12 hours). The plate can then be rinsed as described above. Skilled practitioners will appreciate that many variations of this method are possible. For example, the method can include coating a substrate with a
15 test compound and adding Wnt or FRZ polypeptides to the substrate-bound compound.

Binding of FZD or Wnt to a second compound, e.g., the test compound described above or to a binding partner (e.g., FZD7 to Wnt 3, 8b and/or 11; discussed in further detail below), can be detected by any of a variety of art-known methods. For example, an antibody that specifically binds to a FZD or Wnt polypeptide (i.e., an anti-
20 FZD antibody, e.g., the polyclonal antibody described in the Examples section, or an anti-Wnt antibody) can be used in an immunoassay. If desired, the antibody can be labeled (e.g., fluorescently or with a radioisotope) and detected directly (*see*, e.g., West and McMahon, *J. Cell Biol.* 74:264, 1977). Alternatively, a second antibody can be used for detection (e.g., a labeled antibody that binds to the Fc portion of the anti-FZD
25 or anti-Wnt antibody). In an alternative detection method, the FZD or Wnt polypeptide is labeled (e.g., with a radioisotope, fluorophore, chromophore, or the like), and the label is detected. In still another method, a FZD or Wnt polypeptide is produced as a fusion protein with a protein that can be detected optically, e.g., green fluorescent protein (which can be detected under UV light). In an alternative method, the
30 polypeptide is produced as a fusion protein with an enzyme having a detectable enzymatic activity, such as horseradish peroxidase, alkaline phosphatase, β -galactosidase, or glucose oxidase. Genes encoding all of these enzymes have been cloned and are available for use by skilled practitioners. If desired, the fusion protein

can include an antigen or epitope that can be detected and measured with a polyclonal or monoclonal antibody using conventional methods. Suitable antigens include enzymes (e.g., horse radish peroxidase, alkaline phosphatase, and β -galactosidase) and non-enzymatic polypeptides (e.g., serum proteins, such as BSA and globulins, and milk proteins, such as caseins).

In various methods for identifying polypeptides (e.g., test polypeptides) that bind to a FZD or Wnt polypeptides, the conventional two-hybrid assays of protein/protein interactions can be used (*see* e.g., Chien et al., *Proc. Natl. Acad. Sci. USA*, 88:9578, 1991; Fields et al., U.S. Pat. No. 5,283,173; Fields and Song, *Nature*, 340:245, 1989; Le Douarin et al., *Nucleic Acids Research*, 23:876, 1995; Vidal et al., *Proc. Natl. Acad. Sci. USA*, 93:10315-10320, 1996; and White, *Proc. Natl. Acad. Sci. USA*, 93:10001-10003, 1996). Generally, two-hybrid methods involve reconstitution of two separable domains of a transcription factor. One fusion protein includes the FZD or Wnt polypeptide fused to either a transactivator domain or DNA binding domain of a transcription factor (e.g., of Gal4). The other fusion protein contains a test polypeptide or a binding partner for the polypeptide included in the first fusion protein, fused to either the DNA binding domain or a transactivator domain of a transcription factor. Binding of the FZD or Wnt polypeptide to the test polypeptide or binding partner reconstitutes the transcription factor. Reconstitution of the transcription factor can be detected by detecting expression of a gene (i.e., a reporter gene) that is operably linked to a DNA sequence that is bound by the DNA binding domain of the transcription factor. Kits for practicing various two-hybrid methods are commercially available (e.g., from Clontech; Palo Alto, CA).

In another aspect, the invention includes methods for screening test compounds to identify a compound that modulates a protein-protein interaction between FZD and Wnt polypeptides. A method useful for high throughput screening of compounds capable of modulating protein-protein interactions between transcriptional regulators is described in Lepourcelet et al., *Cancer Cell* 5: 91-102 (2004), which is incorporated herein by reference in its entirety. Typically, a first compound is provided. The first compound is a FZD (e.g., FZD7) or Wnt (e.g., Wnt 3, 8b, or 11) polypeptide or biologically active fragment thereof. A second compound is provided that is different from the first compound and is labeled. The second compound is a FZD (e.g., FZD7) or Wnt (e.g., Wnt 3, 8b, or 11) polypeptide or biologically active fragment thereof. A

test compound is provided. The first compound, second compound and test compound are contacted with each other. The amount of label bound to the first compound is then determined. A change in protein-protein interaction between the first compound and the second compound as assessed by label bound is indicative of the usefulness of the test compound in modulating a protein-protein interaction between the FZD and Wnt polypeptide.

In certain embodiments, the first compound provided is attached to a solid support. Solid supports include, e.g., resins (e.g., agarose and beads) and multiwell plates. In certain embodiments, the method includes a washing step after the contacting step, so as to separate bound and unbound label.

In certain embodiments, a plurality of test compounds is contacted with the first compound and second compound. The different test compounds can be contacted with the other compounds in groups or separately. In certain embodiments, each of the test compounds is contacted with both the first compound and the second compound in an individual well. For example, the method can screen libraries of test compounds. Libraries of test compounds are discussed in detail above. Libraries can include, e.g., natural products, organic chemicals, peptides, and/or modified peptides, including, e.g., D-amino acids, unconventional amino acids, and N-substituted amino acids. Typically, the libraries are in a form compatible with screening in multiwell plates, e.g., 96-well plates. The assay is particularly useful for automated execution in a multiwell format in which many of the steps are controlled by computer and carried out by robotic equipment. The libraries can also be used in other formats, e.g., synthetic chemical libraries affixed to a solid support and available for release into microdroplets.

In certain embodiments, the first compound is a FZD7 polypeptide or fragment thereof and the second compound is a Wnt polypeptide, such as Wnt 3, 8b, or 11, or fragment thereof. In other embodiments, the first compound is a Wnt polypeptide, such as Wnt 3, 8b, or 11 polypeptide or fragment thereof, and the second compound is a FZD7 polypeptide or fragment thereof. The solid support to which the first compound is attached can be, e.g., sepharose beads, SPA beads (microspheres that incorporate a scintillant) or a multiwell plate. SPA beads can be used when the assay is performed without a washing step, e.g., in a scintillation proximity assay. Sepharose beads can be used when the assay is performed with a washing step. The second compound can be labeled with any label that will allow its detection, e.g., a radiolabel, a fluorescent

agent, biotin, a peptide tag, or an enzyme fragment. The second compound can also be radiolabeled, e.g., with ^{125}I or ^3H .

In certain embodiments, the enzymatic activity of an enzyme chemically conjugated to, or expressed as a fusion protein with, the first or second compound, is used to detect bound protein. A binding assay in which a standard immunological method is used to detect bound protein is also included. In certain other embodiments, the interaction of Wnt and FZD polypeptides or fragments thereof is detected by fluorescence resonance energy transfer (FRET) between a donor fluorophore covalently linked to a FZD or Wnt polypeptide (e.g., a fluorescent group chemically conjugated to FZD or Wnt, or a variant of green fluorescent protein (GFP) expressed as an FZD or Wnt-GFP chimeric protein) and an acceptor fluorophore covalently linked to a substrate protein, where there is suitable overlap of the donor emission spectrum and the acceptor excitation spectrum to give efficient nonradiative energy transfer when the fluorophores are brought into close proximity through the protein-protein interaction of FZD and Wnt polypeptides.

In other embodiments, the protein-protein interaction is detected by reconstituting domains of an enzyme, e.g., beta-galactosidase (see Rossi et al, Proc. Natl. Acad. Sci. USA 94:8405-8410 (1997)).

In still other embodiments, the protein-protein interaction is assessed by fluorescence ratio imaging (Bacskai et al, Science 260:222-226 (1993)) of suitable chimeric constructs of FZD and Wnt polypeptides in cells, or by variants of the two-hybrid assay (Fearon et al, Proc Natl Acad Sci USA 89:7958-7962 (1992); Takacs et al, Proc Natl Acad Sci USA 90:10375-10379 (1993); Vidal et al, Proc Natl Acad Sci USA 93:10321-10326 (1996)) employing suitable constructs of FZD and Wnt polypeptides and tailored for a high throughput assay to detect compounds that inhibit the FZD/Wnt interaction. These embodiments have the advantage that the cell permeability of the test compounds is assured.

For example, in one assay, a FZD or Wnt polypeptide or fragment thereof is adsorbed to ELISA plates. The FZD or Wnt polypeptides are then exposed to test compounds, followed by a glutathione-S-transferase (GST)-binding partner fusion protein, e.g., a GST-FZD or -Wnt polypeptide fusion protein. Bound protein is detected with goat anti-GST antibody, alkaline phosphatase (AP)-coupled anti-goat

IgG, and AP substrate. Compounds that interfere with protein-protein interactions yield reduced AP signals in the ELISA plates.

In still another aspect, the invention provides methods of identifying test compounds that modulate (e.g., increase or decrease) expression of a FZD polypeptide.

5 The method includes contacting a FZD nucleic acid with a test compound and then measuring expression of the encoded FZD polypeptide. In a related aspect, the invention features a method of identifying compounds that modulate (e.g., increase or decrease) the expression of FZD polypeptides by measuring expression of a FZD polypeptide in the presence of the test compound or after the addition of the test
10 compound in: (a) a cell line into which has been incorporated a recombinant construct including the FZD nucleic acid sequence or fragment or an allelic variation thereof; or (b) a cell population or cell line that naturally selectively expresses FZD, and then measuring the expression of the FZD protein.

Since the FZD nucleic acids described herein have been identified, they can be
15 cloned into various host cells (e.g., mammalian cells, insect cells, bacteria or fungi) for carrying out such assays in whole cells.

In certain embodiments, an isolated nucleic acid molecule encoding a FZD polypeptide is used to identify a compound that modulates (e.g., increases or decreases) the expression of FZD *in vivo* (e.g., in a FZD-producing cell). In such embodiments,
20 cells that express a FZD (e.g., FZD7 and/or 8) are cultured, exposed to a test compound (or a mixture of test compounds), and the level of FZD expression is compared with the level of FZD expression or activity in cells that are otherwise identical but that have not been exposed to the test compound(s). Standard quantitative assays of gene expression can be used.

25 Expression of FZD can be measured using art-known methods, for example, by Northern blot PCR analysis or RNase protection analyses using a nucleic acid molecule of the invention as a probe. Other examples include enzyme-linked immunosorbent assay (ELISA), radioimmunoassay (RIA) and fluorescent activated cell sorting (FACS). The level of expression in the presence of the test molecule, compared
30 with the level of expression in its absence, will indicate whether or not the test compound modulates the expression of a FZD polypeptide.

In still another aspect, the invention provides methods of screening test compounds utilizing cell systems that are sensitive to perturbation of one or several transcriptional/translational components.

5 In certain embodiments, the methods include identifying candidate compounds that interfere with steps in FZD translational accuracy, such as maintaining a proper reading frame during translation and terminating translation at a stop codon. This method involves constructing cells in which a detectable reporter polypeptide can only be produced if the normal process of staying in one reading frame or of terminating translation at a stop codon has been disrupted. This method further involves contacting
10 the cell with a test compound to examine whether it increases or decreases the production of the reporter polypeptide.

In other embodiments, the cell system is a cell-free extract and the method involves measuring transcription or translation *in vitro*. Conditions are selected so that transcription or translation of the reporter is increased or decreased by the addition of a
15 transcription modifier or a translation modifier to the cell extract.

One method for identifying candidate compounds relies upon a transcription-responsive gene product. This method involves constructing a cell in which the production of a reporter molecule changes (i.e., increases or decreases) under conditions in which cell transcription of a FZD nucleic acid changes (i.e., increases or
20 decreases). Specifically, the reporter molecule is encoded by a nucleic acid transcriptionally linked to a sequence constructed and arranged to cause a relative change in the production of the reporter molecule when transcription of a FZD nucleic acid changes. A gene sequence encoding the reporter may, for example, be fused to part or all of the gene encoding the transcription-responsive gene product and/or to part
25 or all of the genetic elements that control the production of the gene product.

Alternatively, the transcription-responsive gene product may stimulate transcription of the gene encoding the reporter, either directly or indirectly. The method further involves contacting the cell with a test compound, and determining whether the test compound increases or decreases the production of the reporter molecule in the cell.

30 Alternatively, the method for identifying candidate compounds can rely upon a translation-responsive gene product. This method involves constructing a cell in which cell translation of a FZD nucleic acid changes (i.e., increases or decreases). Specifically, the reporter molecule is encoded by nucleic acid translationally linked to a

sequence constructed and arranged to cause a relative increase or decrease in the production of the reporter molecule when transcription of a FZD nucleic acid changes. A gene sequence encoding the reporter may, for example, be fused to part or all of the gene encoding the translation-responsive gene product and/or to part or all of the genetic elements that control the production of the gene product. Alternatively, the translation-responsive gene product may stimulate translation of the gene encoding the reporter, either directly or indirectly. The method further involves contacting the cell with a test compound, and determining whether the test compound increases or decreases the production of the first reporter molecule in the cell.

For these and any method described herein, a wide variety of reporters may be used, with typical reporters providing conveniently detectable signals (e.g., by spectroscopy). By way of example, a reporter gene may encode an enzyme that catalyses a reaction that alters light absorption properties.

Examples of reporter molecules include but are not limited to β -galactosidase, invertase, green fluorescent protein, luciferase, chloramphenicol acetyltransferase, beta-glucuronidase, exo-glucanase, glucoamylase and radiolabeled reporters. For example, the production of the reporter molecule can be measured by the enzymatic activity of the reporter gene product, such as β -galactosidase.

Any of the methods described herein can be used for high throughput screening of numerous test compounds to identify candidate anti-cancer agents. By high-throughput screening is meant that the method can be used to screen a large number of candidate compounds relatively easily and quickly.

Having identified a test compound as a candidate anti-cancer agent, the compound can be further tested *in vivo* or *in vitro* using techniques known in the art to confirm whether it is an anti-cancer agent, e.g., to determine whether it can treat cancer, modulate Wnt/FZD signaling, modulate cancer cell motility and/or modulate FZD expression *in vitro* (e.g., using isolated cells or cell-free systems) or *in vivo* (e.g., using an animal, e.g., rodent, model system) if desired.

In vitro testing of a candidate compound can be accomplished by means known to those in the art, such as assays involving the use of cells, e.g., wild type, cancerous and/or transgenic liver cells. Exemplary assays for monitoring Wnt/FZD signaling, FZD expression and cancer cell motility, as well as useful cells that can be used in such assays, are described in the Examples section, below.

Alternatively or in addition, *in vivo* testing of candidate compounds can be performed by means known to those in the art. For example, the candidate compound(s) can be administered to a mammal, such as a rodent (e.g., mouse) or rabbit. Such animal model systems are art-accepted for testing potential
5 pharmaceutical agents to determine their therapeutic efficacy in patients, e.g., human patients. Animals that are particularly useful for *in vivo* testing are wild type animals or non-wild type animals (e.g., mice) that over-produce FZD polypeptides, e.g., animals that overexpress a FZD transgene (e.g., a FZD7 transgene) and/or that display reduced production of FZD8 polypeptides. Other animals that are useful for *in vivo* testing are
10 animals bred to develop liver cancer. Certain particularly useful transgenic mice that develop liver cancer are described in the Examples section and are included in the present invention.

In a typical *in vivo* assay, an animal (e.g., a wild type or transgenic mouse) is administered, by any route deemed appropriate (e.g., by injection), a dose of a
15 candidate compound. Conventional methods and criteria can then be used to monitor animals for the desired activity. If needed, the results obtained in the presence of the candidate compound can be compared with results in control animals that are not treated with the test compound.

20 Medicinal Chemistry

Once a compound (or agent) of interest has been identified, standard principles of medicinal chemistry can be used to produce derivatives of the compound for further rounds of testing. Derivatives can be screened for improved pharmacological properties, for example, efficacy, pharmaco-kinetics, stability, solubility, and clearance.
25 The moieties responsible for a compound's activity in the assays described above can be delineated by examination of structure-activity relationships (SAR) as is commonly practiced in the art. A person of ordinary skill in pharmaceutical chemistry could modify moieties on a candidate compound or agent and measure the effects of the modification on the efficacy of the compound or agent to thereby produce derivatives
30 with increased potency. For an example, see Nagarajan *et al.* (1988) *J. Antibiot.* 41: 1430-8. Furthermore, if the biochemical target of the compound (or agent) is known or determined, the structure of the target and the compound can inform the design and

optimization of derivatives. Molecular modeling software is commercially available (e.g., Molecular Simulations, Inc.) for this purpose.

IV. Antibodies

5 The invention features purified or isolated antibodies that bind, e.g., specifically bind, to a FZD and/or Wnt polypeptide, i.e., anti-FZD and anti-Wnt antibodies. An antibody "specifically binds" to a particular antigen, e.g., a FZD7 and/or 8 polypeptide, when it binds to that antigen, but recognizes and binds to a lesser extent (e.g., does not recognize and bind) to other molecules in a sample. Antibodies of the invention
10 include monoclonal antibodies, polyclonal antibodies, humanized or chimeric antibodies, single chain antibodies, Fab fragments, F(ab')₂ fragments, and molecules produced using a Fab expression library.

 An example of a type of antibody included in the present invention is the polyclonal anti-FZD7 antibody described in the Examples section, below. Methods for
15 producing polyclonal antibodies are well known to those of skill in the art.

 As used herein, the term "antibody" refers to a protein comprising at least one, e.g., two, heavy (H) chain variable regions (abbreviated herein as VH), and at least one, e.g., two light (L) chain variable regions (abbreviated herein as VL). The VH and VL regions can be further subdivided into regions of hypervariability, termed
20 "complementarity determining regions" ("CDR"), interspersed with regions that are more conserved, termed "framework regions" (FR). The extent of the framework region and CDR's has been precisely defined (see, Kabat, E.A., *et al.* (1991) *Sequences of Proteins of Immunological Interest, Fifth Edition*, U.S. Department of Health and Human Services, NIH Publication No. 91-3242, and Chothia, C. *et al.* (1987) *J. Mol.*
25 *Biol.* 196:901-917). Each VH and VL is composed of three CDR's and four FRs, arranged from amino-terminus to carboxy-terminus in the following order: FR1, CDR1, FR2, CDR2, FR3, CDR3, FR4.

 An anti-FZD or -Wnt antibody can further include a heavy and light chain constant region, to thereby form a heavy and light immunoglobulin chain, respectively.
30 The antibody can be a tetramer of two heavy immunoglobulin chains and two light immunoglobulin chains, wherein the heavy and light immunoglobulin chains are interconnected by, e.g., disulfide bonds. The heavy chain constant region is comprised of three domains, CH1, CH2, and CH3. The light chain constant region is comprised of

one domain, CL. The variable region of the heavy and light chains contains a binding domain that interacts with an antigen. The constant regions of the antibodies typically mediate the binding of the antibody to host tissues or factors, including various cells of the immune system (e.g., effector cells) and the first component (Clq) of the classical complement system.

A “FZD binding fragment” and “Wnt binding fragment” of an antibody refers to one or more fragments of a full-length antibody that retain the ability to specifically bind to FZD or Wnt polypeptides, respectively, or to portions thereof. Examples of polypeptide binding fragments of an antibody include, but are not limited to: (i) a Fab fragment, a monovalent fragment consisting of the VL, VH, CL and CH1 domains; (ii) a F(ab')₂ fragment, a bivalent fragment comprising two Fab fragments linked by a disulfide bridge at the hinge region; (iii) a Fd fragment consisting of the VH and CH1 domains; (iv) a Fv fragment consisting of the VL and VH domains of a single arm of an antibody, (v) a dAb fragment (Ward *et al.*, (1989) *Nature* 341:544-546), which consists of a VH domain; and (vi) an isolated complementarity determining region (CDR). Furthermore, although the two domains of the Fv fragment, VL and VH, are encoded by separate genes, they can be joined, using recombinant methods, by a synthetic linker that enables them to be made as a single protein chain in which the VL and VH regions pair to form monovalent molecules (known as single chain Fv (scFv); see *e.g.*, Bird *et al.* (1988) *Science* 242:423-426; and Huston *et al.* (1988) *Proc. Natl. Acad. Sci. USA* 85:5879-5883). Such single chain antibodies are also encompassed within the terms “FZD binding fragment” and “Wnt binding fragment” of an antibody. These antibody fragments can be obtained using conventional techniques known to those with skill in the art.

To produce antibodies, polypeptides (or antigenic fragments (e.g., fragments of a polypeptide that appear likely to be antigenic by criteria such as high frequency of charged residues) or analogs of such polypeptides), e.g., those produced by recombinant or peptide synthetic techniques (see, *e.g.*, *Solid Phase Peptide Synthesis*, *supra*; Ausubel *et al.*, *supra*), can be used. In general, the polypeptides can be coupled to a carrier protein, such as KLH, as described in Ausubel *et al.*, *supra*, mixed with an adjuvant, and injected into a host mammal. A “carrier” is a substance that confers stability on, and/or aids or enhances the transport or immunogenicity of, an associated molecule. For example, FZD or Wnt proteins, or fragments thereof, can be generated

using standard techniques of PCR, and can be cloned into a pGEX expression vector (Ausubel et al., supra). Fusion proteins can be expressed in *E. coli* and purified using a glutathione agarose affinity matrix as described in Ausubel et al., supra.

Typically, various host animals are injected with FZD and/or Wnt polypeptides. Examples of suitable host animals include rabbits, mice, guinea pigs, and rats. Various adjuvants can be used to increase the immunological response, depending on the host species, including but not limited to Freund's (complete and incomplete adjuvant), adjuvant mineral gels such as aluminum hydroxide, surface active substances such as lysolecithin, pluronic polyols, polyanions, peptides, oil emulsions, keyhole limpet hemocyanin, dinitrophenol, BCG (bacille Calmette-Guerin) and *Corynebacterium parvum*. Such procedures result in the production of polyclonal antibodies, i.e., heterogeneous populations of antibody molecules derived from the sera of the immunized animals. Antibodies can be purified from blood obtained from the host animal, for example, by affinity chromatography methods in which FZD and/or Wnt polypeptide antigens are immobilized on a resin.

The present invention also includes anti-FZD and anti-Wnt monoclonal antibodies. Monoclonal antibodies (mAbs), which are homogeneous populations of antibodies specific for a particular antigen, can be prepared using FZD or Wnt polypeptides and standard hybridoma technology (see, e.g., Kohler et al., *Nature*, 256:495, 1975; Kohler et al., *Eur. J. Immunol.*, 6:511, 1976; Kohler et al., *Eur. J. Immunol.*, 6:292, 1976; Hammerling et al., In Monoclonal Antibodies and T Cell Hybridomas, Elsevier, NY, 1981; Ausubel et al., supra).

Typically, monoclonal antibodies are produced using any technique that provides for the production of antibody molecules by continuous cell lines in culture, such as those described in Kohler et al., *Nature*, 256:495, 1975, and U.S. Patent No. 4,376,110; the human B-cell hybridoma technique (Kosbor et al., *Immunology Today*, 4:72, 1983; Cole et al., *Proc. Natl. Acad. Sci. USA*, 80:2026, 1983); and the EBV-hybridoma technique (Cole et al., Monoclonal Antibodies and Cancer Therapy, Alan R. Liss, Inc., pp. 77-96, 1983). Such antibodies can be of any immunoglobulin class including IgG, IgM, IgE, IgA, IgD, and any subclass thereof. The hybridomas producing the mAbs of this invention can be cultivated *in vitro* or *in vivo*.

Once produced, polyclonal or monoclonal antibodies can be tested for recognition, e.g., specific recognition, of FZD or Wnt polypeptides in an immunoassay,

such as a Western blot or immunoprecipitation analysis using standard techniques, e.g., as described in Ausubel et al., supra. Antibodies that specifically bind to FZD or Wnt polypeptides (e.g., FZD7, FZD8, Wnt 3, Wnt 8b and/or Wnt 11) are useful in the invention. For example, such antibodies can be used in an immunoassay to detect the polypeptide in a sample, e.g., a tissue sample.

Alternatively or in addition, a monoclonal antibody can be produced recombinantly, e.g., produced by phage display or by combinatorial methods as described in, e.g., Ladner et al. U.S. Patent No. 5,223,409; Kang et al. International Publication No. WO 92/18619; Dower et al. International Publication No. WO 91/17271; Winter et al. International Publication WO 92/20791; Markland et al. International Publication No. WO 92/15679; Breitling et al. International Publication WO 93/01288; McCafferty et al. International Publication No. WO 92/01047; Garrard et al. International Publication No. WO 92/09690; Ladner et al. International Publication No. WO 90/02809; Fuchs et al. (1991) *Bio/Technology* 9:1370-1372; Hay et al. (1992) *Hum Antibod Hybridomas* 3:81-85; Huse et al. (1989) *Science* 246:1275-1281; Griffiths et al. (1993) *EMBO J* 12:725-734; Hawkins et al. (1992) *J Mol Biol* 226:889-896; Clackson et al. (1991) *Nature* 352:624-628; Gram et al. (1992) *PNAS* 89:3576-3580; Garrard et al. (1991) *Bio/Technology* 9:1373-1377; Hoogenboom et al. (1991) *Nuc Acid Res* 19:4133-4137; and Barbas et al. (1991) *PNAS* 88:7978-7982.

Anti-FZD and -Wnt antibodies can be fully human antibodies (e.g., an antibody made in a mouse which has been genetically engineered to produce an antibody from a human immunoglobulin sequence), or non-human antibodies, e.g., rodent (mouse or rat), rabbit, horse, cow, goat, primate (e.g., monkey), camel, donkey, pig, or bird antibodies.

An anti-FZD and anti-Wnt antibody can be one in which the variable region, or a portion thereof, e.g., the CDRs, is generated in a non-human organism, e.g., a rat or mouse. The anti-FZD and anti-Wnt antibody can also be, for example, chimeric, CDR-grafted, or humanized antibodies. The anti-FZD and anti-Wnt antibody can also be generated in a non-human organism, e.g., a rat or mouse, and then modified, e.g., in the variable framework or constant region, to decrease antigenicity in a human.

Techniques developed for the production of "chimeric antibodies" (Morrison et al., *Proc. Natl. Acad. Sci.*, 81:6851, 1984; Neuberger et al., *Nature*, 312:604, 1984; Takeda et al., *Nature*, 314:452, 1984) can be used to splice the genes from a mouse

antibody molecule of appropriate antigen specificity together with genes from a human antibody molecule of appropriate biological activity. A chimeric antibody is a molecule in which different portions are derived from different animal species, such as those having a variable region derived from a murine mAb and a human immunoglobulin constant region.

Alternatively, techniques described for the production of single chain antibodies (U.S. Patent 4,946,778; and U.S. Patents 4,946,778 and 4,704,692) can be adapted to produce single chain antibodies specific for a FZD or Wnt polypeptide. Single chain antibodies are formed by linking the heavy and light chain fragments of the Fv region via an amino acid bridge, resulting in a single chain polypeptide.

Antibody fragments that recognize and bind to specific epitopes can be generated by known techniques. For example, such fragments can include but are not limited to F(ab')₂ fragments, which can be produced by pepsin digestion of the antibody molecule, and Fab fragments, which can be generated by reducing the disulfide bridges of F(ab')₂ fragments. Alternatively, Fab expression libraries can be constructed (Huse et al., *Science*, 246:1275, 1989) to allow rapid and easy identification of monoclonal Fab fragments with the desired specificity.

Polyclonal and monoclonal antibodies (or fragments thereof) that specifically bind to a FZD and/or Wnt polypeptides can be used, for example, to detect expression of FZD and/or Wnt in various tissues of a patient. For example, a FZD7 and/or 8 polypeptide can be detected in conventional immunoassays of biological tissues or extracts. Examples of suitable assays include, without limitation, Western blotting, ELISAs, radioimmunoassays, and the like.

V. Pharmaceutical Compositions

Any pharmaceutically active compound, agent, nucleic acid, polypeptide, or antibody (all of which can be referred to herein as "active compounds"), can be incorporated into pharmaceutical compositions. Such compositions typically include the active compound and a pharmaceutically acceptable carrier. A "pharmaceutically acceptable carrier" can include solvents, dispersion media, coatings, antibacterial and antifungal agents, isotonic and absorption delaying agents, and the like, compatible with pharmaceutical administration. Supplementary active compounds can also be incorporated into the compositions.

A pharmaceutical composition can be formulated to be compatible with its intended route of administration. Examples of routes of administration include enteral (e.g., oral or rectal) and parenteral, e.g., intravenous (e.g., into the portal vein of the liver), intradermal, subcutaneous, transdermal, transmucosal, and pulmonary
5 administration. Administration may be directly into the liver, e.g., by injection or by topical administration during surgery. Solutions or suspensions used for injection can include the following components: a sterile diluent such as water for injection, saline solution, fixed oils, polyethylene glycols, glycerine, propylene glycol or other synthetic solvents; antibacterial agents such as benzyl alcohol or methyl parabens; antioxidants
10 such as ascorbic acid or sodium bisulfite; chelating agents such as ethylenediaminetetraacetic acid; buffers such as acetates, citrates or phosphates and agents for the adjustment of tonicity such as sodium chloride or dextrose. pH can be adjusted with acids or bases, such as hydrochloric acid or sodium hydroxide. The parenteral preparation can be enclosed in ampoules, disposable syringes or multiple
15 dose vials made of glass or plastic.

Pharmaceutical compositions suitable for injectable use include sterile aqueous solutions (where water soluble) or dispersions and sterile powders for the extemporaneous preparation of sterile injectable solutions or dispersion. For intravenous administration, suitable carriers include physiological saline, bacteriostatic
20 water, Cremophor EL™ (BASF, Parsippany, NJ) or phosphate buffered saline (PBS). In all cases, the composition must be sterile and should be fluid to the extent that easy syringability exists. It should be stable under the conditions of manufacture and storage and must be preserved against the contaminating action of microorganisms such as bacteria and fungi. The carrier can be a solvent or dispersion medium containing, for
25 example, water, ethanol, polyol (for example, glycerol, propylene glycol, liquid polyetheylene glycol, and the like), and suitable mixtures thereof. The proper fluidity can be maintained, for example, by the use of a coating such as lecithin, by the maintenance of the required particle size in the case of dispersion and by the use of surfactants. Prevention of the action of microorganisms can be achieved by various
30 antibacterial and antifungal agents, for example, parabens, chlorobutanol, phenol, ascorbic acid, thimerosal, and the like. In many cases, it will be preferable to include isotonic agents, for example, sugars, polyalcohols such as mannitol or sorbitol and sodium chloride. Prolonged absorption of the injectable compositions can be achieved

by including an agent which delays absorption, e.g., aluminum monostearate and gelatin.

5 Sterile injectable solutions can be prepared by incorporating the active compound in the required amount in an appropriate solvent with one or a combination of ingredients enumerated above, as required, followed by filtered sterilization. Generally, dispersions are prepared by incorporating the active compound into a sterile vehicle which contains a basic dispersion medium and the required other ingredients from those enumerated above. In the case of sterile powders for the preparation of sterile injectable solutions, the preferred methods of preparation are vacuum drying and
10 freeze-drying, which yield a powder of the active ingredient plus any additional desired ingredient from a previously sterile-filtered solution thereof.

Oral compositions generally include an inert diluent or an edible carrier. For the purpose of oral therapeutic administration, the active compound can be incorporated with excipients and used in the form of tablets, troches, or capsules, e.g., gelatin
15 capsules. Oral compositions can also be prepared using a fluid carrier for use as a mouthwash. Pharmaceutically compatible binding agents, and/or adjuvant materials can be included as part of the composition. The tablets, pills, capsules, troches and the like can contain any of the following ingredients, or compounds of a similar nature: a binder such as microcrystalline cellulose, gum tragacanth or gelatin; an excipient such
20 as starch or lactose, a disintegrating agent such as alginic acid, Primogel, or corn starch; a lubricant such as magnesium stearate or Sterotes; a glidant such as colloidal silicon dioxide; a sweetening agent such as sucrose or saccharin; or a flavoring agent such as peppermint, methyl salicylate, or orange flavoring.

For administration by inhalation, the compounds are delivered in the form of an
25 aerosol spray from a pressured container or dispenser that contains a suitable propellant, e.g., a gas such as carbon dioxide, or a nebulizer.

Systemic administration can also be by transmucosal or transdermal means. For transmucosal or transdermal administration, penetrants appropriate to the barrier to be permeated are used in the formulation. Such penetrants are generally known in the art,
30 and include, for example, for transmucosal administration, detergents, bile salts, and fusidic acid derivatives. Transmucosal administration can be accomplished through the use of nasal sprays or suppositories (e.g., with conventional suppository bases such as cocoa butter and other glycerides). For transdermal administration, the active

compounds are formulated into ointments, salves, gels, or creams as generally known in the art.

In one embodiment, the active compounds are prepared with carriers that will protect the compound against rapid elimination from the body, such as a controlled
5 release formulation, including implants and microencapsulated delivery systems. Biodegradable, biocompatible polymers can be used, such as ethylene vinyl acetate, polyanhydrides, polyglycolic acid, collagen, polyorthoesters, and polylactic acid. Methods for preparation of such formulations will be apparent to those skilled in the art. The materials can also be obtained commercially from Alza Corporation and Nova
10 Pharmaceuticals, Inc. Liposomal suspensions can also be used as pharmaceutically acceptable carriers. These can be prepared according to methods known to those skilled in the art, for example, as described in U.S. Patent No. 4,522,811.

It may be advantageous to formulate oral or parenteral compositions in dosage unit form for ease of administration and uniformity of dosage. Dosage unit form as
15 used herein refers to physically discrete units suited as unitary dosages for the subject to be treated; each unit containing a predetermined quantity of active compound calculated to produce the desired therapeutic effect in association with the required pharmaceutical carrier.

Toxicity and therapeutic efficacy of such compounds can be determined by
20 standard pharmaceutical procedures in cell cultures or experimental animals, *e.g.*, for determining the LD₅₀ (the dose lethal to 50% of the population) and the ED₅₀ (the dose therapeutically effective in 50% of the population). The dose ratio between toxic and therapeutic effects is the therapeutic index, and it can be expressed as the ratio LD₅₀/ED₅₀. Compounds which exhibit high therapeutic indices are preferred. While
25 compounds that exhibit toxic side effects may be used, care should be taken to design a delivery system that targets such compounds to the site of affected tissue, *e.g.*, liver, in order to minimize potential damage to healthy cells and, thereby, reduce side effects.

The data obtained from cell culture assays and animal studies can be used in formulating a range of dosage for use in humans. The dosage of such compounds lies
30 preferably within a range of circulating concentrations that include the ED₅₀ with little or no toxicity. The dosage may vary within this range depending upon the dosage form employed and the route of administration utilized. For any compound used in the method of the invention, the therapeutically effective dose can be estimated initially

from cell culture assays. A dose may be formulated in animal models to achieve a circulating plasma concentration range that includes the IC₅₀ (i.e., the concentration of the test compound that achieves a half-maximal inhibition of symptoms) as determined in cell culture. Such information can be used to more accurately determine useful
5 doses in humans. Levels in plasma may be measured, for example, by high performance liquid chromatography.

The terms "effective amount" and "effective to treat," as used herein, refer to an amount or concentration of a compound described herein utilized for a period of time (including acute or chronic administration and periodic or continuous
10 administration) that is effective within the context of its administration for causing an intended effect or physiological outcome. For compounds described herein, an effective amount, e.g., of a polypeptide (i.e., an effective dosage), ranges from about 0.001 to 500 mg/kg body weight, e.g. about 0.01 to 50 mg/kg body weight, e.g. about 0.1 to 20 mg/kg body weight. The polypeptide can be administered one time per week
15 for between about 1 to 10 weeks, e.g. between 2 to 8 weeks, about 3 to 7 weeks, or for about 4, 5, or 6 weeks. The skilled artisan will appreciate that certain factors influence the dosage and timing required to effectively treat a patient, including but not limited to the type of patient to be treated, the severity of the disease or disorder, previous treatments, the general health and/or age of the patient, and other diseases present.
20 Moreover, treatment of a patient with a therapeutically effective amount of a compound can include a single treatment or, preferably, can include a series of treatments.

With respect to antibodies, partially human antibodies and fully human antibodies have a longer half-life within the human body than other antibodies. Accordingly, lower dosages and less frequent administration are possible.
25 Modifications such as lipidation can be used to stabilize antibodies and to enhance uptake and tissue penetration. A method for lipidation of antibodies is described by Cruikshank *et al.* ((1997) *J. Acquired Immune Deficiency Syndromes and Human Retrovirology* 14:193).

If the compound is a small molecule, exemplary doses include milligram or
30 microgram amounts of the small molecule per kilogram of subject or sample weight (e.g., about 1 microgram per kilogram to about 500 milligrams per kilogram, about 100 micrograms per kilogram to about 5 milligrams per kilogram, or about 1 microgram per kilogram to about 50 micrograms per kilogram. It is furthermore understood that

appropriate doses of a small molecule depend upon the potency of the small molecule with respect to the expression or activity to be modulated. When one or more of these small molecules is to be administered to an animal (e.g., a human) to modulate expression or activity of a FZD or Wnt polypeptide or nucleic acid, a physician, 5 veterinarian, or researcher may, for example, prescribe a relatively low dose at first, subsequently increasing the dose until an appropriate response is obtained. In addition, it is understood that the specific dose level for any particular animal subject will depend upon a variety of factors including the activity of the specific compound employed, the age, body weight, general health, gender, and diet of the subject, the time of 10 administration, the route of administration, the rate of excretion, any drug combination, and the degree of expression or activity to be modulated.

Nucleic acid molecules (e.g., FZD, e.g., FZD7, DNA) can be inserted into vectors and used as gene therapy vectors. Gene therapy vectors can be delivered to a subject by, for example, intravenous injection, local administration (see, e.g., U.S. 15 Patent 5,328,470) or by stereotactic injection (see, e.g., Chen *et al.* (1994) *Proc. Natl. Acad. Sci. USA* 91:3054-3057). The pharmaceutical preparation of the gene therapy vector can include the gene therapy vector in an acceptable diluent, or can comprise a slow release matrix in which the gene delivery vehicle is imbedded. Alternatively, where the complete gene delivery vector can be produced intact from recombinant 20 cells, e.g., retroviral vectors, the pharmaceutical preparation can include one or more cells which produce the gene delivery system. Exemplary constructs that can potentially be used in gene therapy methods are described in the Examples section, below.

The pharmaceutical compositions can be included in a container, pack, or 25 dispenser together with instructions for administration.

VI. Cancer and Treatments Therefor

The term "cancer" refers to animal cells having the capacity for autonomous growth. Examples of such cells include cells having an abnormal state or condition 30 characterized by rapidly proliferating cell growth. The term is meant to include cancerous growths, e.g., tumors; oncogenic processes, metastatic tissues, and malignantly transformed cells, tissues, or organs, irrespective of histopathologic type or stage of invasiveness. Also included are malignancies of the various organ systems,

such as respiratory, cardiovascular, renal, reproductive, hematological, neurological, hepatic, gastrointestinal, and endocrine systems; as well as adenocarcinomas which include malignancies such as most colon cancers, renal-cell carcinoma, prostate cancer and/or testicular tumors, non-small cell carcinoma of the lung, cancer of the small intestine, and cancer of the esophagus. Cancer that is “naturally arising” includes any cancer that is not experimentally induced by implantation of cancer cells into a subject, and includes, for example, spontaneously arising cancer, cancer caused by exposure of a patient to a carcinogen(s), cancer resulting from insertion of a transgenic oncogene or knockout of a tumor suppressor gene, and cancer caused by infections, e.g., viral infections. The term “carcinoma” is art recognized and refers to malignancies of epithelial or endocrine tissues. The term includes carcinosarcomas, which include malignant tumors composed of carcinomatous and sarcomatous tissues. An “adenocarcinoma” refers to a carcinoma derived from glandular tissue or in which the tumor cells form recognizable glandular structures. The term “hepatocellular carcinoma” (HCC) refers to cancer that arises from hepatocytes, the major cell type of the liver.

The term “patient” is used throughout the specification to describe an animal, human or non-human, rodent or non-rodent, to whom treatment according to the methods of the present invention is provided. Veterinary and human clinical applications are contemplated. The term “patient” includes, but is not limited to, birds, reptiles, amphibians, and mammals, e.g., humans, other primates, pigs, rodents such as mice and rats, rabbits, guinea pigs, hamsters, cows, horses, cats, dogs, sheep and goats. Preferred subjects are humans, farm animals, and domestic pets such as cats and dogs. The term “treat(ment),” is used herein to denote delaying the onset of, inhibiting, alleviating the effects of, or prolonging the life of a patient suffering from, a condition, e.g., cancer.

Cancers that may be treated using the methods and compositions of the present invention include, but are not limited to, cancers of the liver, stomach, colon, rectum, mouth/pharynx, esophagus, larynx, pancreas, lung, small bowel, and bile ducts, among others.

Individuals considered at risk for developing cancer may benefit particularly from the invention, primarily because prophylactic treatment can begin before there is any evidence of a tumor. Individuals “at risk” include, e.g., individuals exposed to

carcinogens, e.g., by consumption, e.g., by inhalation and/or ingestion, at levels that have been shown statistically to promote cancer in susceptible individuals. Also included are individuals exposed to a virus, e.g., a hepatitis virus, e.g., hepatitis B virus (HBV). Also included are individuals at risk due to exposure to ultraviolet radiation, or
5 their environment, occupation, and/or heredity, as well as those who show signs of a precancerous condition. Similarly, individuals in very early stages of cancer or development of metastases (i.e., only one or a few aberrant cells are present in the individual's body or at a particular site in an individual's tissue)) may benefit from such prophylactic treatment.

10 Skilled practitioners will appreciate that a patient can be diagnosed by a physician (or veterinarian, as appropriate for the patient being diagnosed) as suffering from or at risk for cancer using the methods described herein, optionally using additional methods, e.g., assessing a patient's medical history, performing other diagnostic tests and/or by employing imaging techniques.

15 One strategy for treating patients suffering from or at risk for cancer is to modulate Wnt/FZD signaling in the patient. The goal is to increase signaling where signaling is too low and to decrease signaling where signaling is too high. Modulation of Wnt/FZD signaling falls into two basic categories: decreasing (i.e., reducing, e.g., eliminating) Wnt/FZD signaling and increasing (i.e., supplementing or providing)
20 Wnt/FZD signaling where there is insufficient or no activity. Whether Wnt/FZD signaling should be inhibited or increased depends upon the intended application. Wnt/FZD signaling can be modulated using the active compounds (e.g., candidate compounds and/or anti-cancer agents) described herein. Compounds that decrease Wnt/FZD signaling activity, e.g., by decreasing expression of FZD7 and/or interfering
25 with an interaction between FZD7 and its ligand (e.g., Wnt 3, 8b and/or 11) can be used, e.g., as treatments for cancer, e.g., liver cancer. Compounds that increase activity, e.g., by increasing expression of FZD8 can also be used, e.g., as treatments for cancer, e.g., liver cancer.

30 *Decreasing Wnt/FZD Signaling*

Art-known methods for decreasing the expression of a particular protein in a patient can be used to decrease Wnt/FZD signaling. For example, an antisense nucleic acid effective to inhibit expression of an endogenous FZD gene, e.g., FZD7 gene, can

be utilized. As used herein, the term “antisense oligonucleotide” or “antisense” describes an oligonucleotide that is an oligoribonucleotide, oligodeoxyribonucleotide, modified oligoribonucleotide, or modified oligodeoxyribonucleotide which hybridizes under physiological conditions to DNA comprising a particular gene or to an mRNA transcript of that gene and, thereby, inhibits the transcription of that gene and/or the translation of that mRNA.

Antisense molecules are designed so as to interfere with transcription or translation of a target gene (e.g., a gene encoding FZD7 or Wnt 3, 8b or 11) upon hybridization with the target gene or transcript. The antisense nucleic acid can include a nucleotide sequence complementary to an entire FZD or Wnt RNA or only a portion of the RNA. On one hand, the antisense nucleic acid needs to be long enough to hybridize effectively with FZD or Wnt RNA. Therefore, the minimum length is approximately 12 to 25 nucleotides. On the other hand, as length increases beyond about 150 nucleotides, effectiveness at inhibiting translation may increase only marginally, while difficulty in introducing the antisense nucleic acid into target cells may increase significantly. Accordingly, an appropriate length for the antisense nucleic acid may be from about 15 to about 150 nucleotides, e.g., 20, 25, 30, 35, 40, 45, 50, 60, 70, or 80 nucleotides. The antisense nucleic acid can be complementary to a coding region of FZD or Wnt mRNA or a 5' or 3' non-coding region of a FZD mRNA, or both. One approach is to design the antisense nucleic acid to be complementary to a region on both sides of the translation start site of the FZD or Wnt mRNA.

Based upon the sequences disclosed herein, one of skill in the art can easily choose and synthesize any of a number of appropriate antisense molecules for use in accordance with the present invention. For example, a “gene walk” comprising a series of oligonucleotides of 15-30 nucleotides complementary to and spanning the length of a FZD mRNA can be prepared, followed by testing for inhibition of FZD or Wnt expression. Optionally, gaps of 5-10 nucleotides can be left between the oligonucleotides to reduce the number of oligonucleotides synthesized and tested.

The antisense nucleic acid can be chemically synthesized, e.g., using a commercial nucleic acid synthesizer according to the vendor's instructions. Alternatively, the antisense nucleic acids can be produced using recombinant DNA techniques. An antisense nucleic acid can incorporate only naturally occurring nucleotides. Alternatively, it can incorporate variously modified nucleotides or

nucleotide analogs to increase its *in vivo* half-life or to increase the stability of the duplex formed between the antisense molecule and its target RNA. Examples of nucleotide analogs include phosphorothioate derivatives and acridine-substituted nucleotides. Given the description of the targets and sequences, the design and
5 production of suitable antisense molecules is within ordinary skill in the art. For guidance concerning antisense nucleic acids, see, e.g., Goodchild, "Inhibition of Gene Expression by Oligonucleotides," in *Topics in Molecular and Structural Biology, Vol. 12: Oligodeoxynucleotides* (Cohen, ed.), MacMillan Press, London, pp. 53-77 (1989).

Delivery of antisense oligonucleotides can be accomplished by any method
10 known to those of skill in the art. For example, delivery of antisense oligonucleotides for cell culture and/or *ex vivo* work can be performed by standard methods such as the liposome method or simply by addition of membrane-permeable oligonucleotides.

Delivery of antisense oligonucleotides for *in vivo* applications can be accomplished, for example, via local injection of the antisense oligonucleotides at a
15 selected site, e.g., a liver. This method has previously been demonstrated for psoriasis growth inhibition and for cytomegalovirus inhibition. See, for example, Wraight et al., (2001). *Pharmacol Ther.* 90(1):89-104; Anderson et al., (1996) *Antimicrob Agents Chemother* 40: 2004-2011; and Crooke et al., (1996) *J Pharmacol Exp Ther* 277: 923-937.

20 Similarly, RNA interference (RNAi) techniques can be used to inhibit FZD or Wnt expression, in addition or as an alternative to the use of antisense techniques. For example, small interfering RNA (siRNA) duplexes directed against FZD or Wnt nucleic acids could be synthesized and used to prevent expression of the encoded protein(s).

25 Another approach to inhibiting Wnt/FZD signaling involves administering to a patient a candidate compound or anti-cancer agent that binds to FZD polypeptides (e.g., FZD7 polypeptides) and/or their binding partners (e.g., Wnt 3, 8b and/or 11), thereby preventing interaction between the two. Such compounds and agents may, for example, bind to the FZD polypeptide (e.g., to the CRD domain of the FZD
30 polypeptide) and/or to the Wnt polypeptide (e.g., to a binding domain of the Wnt polypeptide) in such a way that interaction between the proteins is prevented. Such candidate compounds and anti-cancer agents can be identified using screening methods described herein. An example of a compound that can bind to a Wnt polypeptide, e.g.,

Wnt 3, 8b and/or 11, is a FZD7 receptor or truncated form thereof, as described in the Examples section, below.

Yet another approach to inhibiting Wnt/FZD signaling involves administering to a patient a vector (e.g., a gene therapy vector) that encodes a mutated (e.g., truncated) form of a FZD receptor, e.g., a FZD7 receptor. Expression of the mutated form of the receptor by the patient's cells that incorporate the construct can interfere with Wnt/FZD signaling in the cells. For example, a construct that encodes a secreted and soluble form of a FZD receptor (e.g., a FZD7 receptor) can be used. Expression of such a construct by target cells would cause the cells to secrete a soluble form of the FZD receptor that would bind Wnt polypeptides, rendering them unable to bind to intact FZD receptors on the cell surface. Alternatively or in addition, a construct that encodes a membrane bound but inactive form of a FZD receptor (i.e., a mutant FZD receptor unable to perform some function performed by a counterpart wild-type FZD receptor) can be used. Expression of such a construct by target cells may bind up Wnt polypeptides or interfere with Wnt/FZD signaling via an internal mechanism not involving Wnt polypeptides. The vector can be derived from a non-replicating linear or circular DNA or RNA vector, or from an autonomously replicating plasmid or viral vector. Methods for constructing suitable expression vectors are known in the art, and useful materials are commercially available. Exemplary expression vectors that encode useful mutated FZD7 polypeptides are described in the Examples section, below.

Increasing Wnt/FZD Signaling

New or supplemental Wnt/FZD signaling can be provided *in vivo* by increasing expression of FZD polypeptides (e.g., FZD8 polypeptides) in the patient. For example, a FZD polypeptide can be generated directly within an organism, e.g., a human, by expressing within the cells of the organism a nucleic acid construct containing a nucleotide sequence encoding a FZD polypeptide (e.g., a FZD8 polypeptide). Any appropriate expression vector suitable for transfecting the cells of the organism of interest can be used for such purposes.

VII. Transgenic Animals

The present invention also features transgenic animals that develop liver cancer and overexpress FZD7 in their liver cells. Such animals represent model systems for

the study of liver cancer and for the development of therapeutic agents that can modulate Wnt/FZD signaling and treat cancer.

Transgenic animals can be, for example, farm animals (pigs, goats, sheep, cows, horses, rabbits, and the like), rodents (such as rats, guinea pigs, and mice), non-human primates (for example, baboons, monkeys, and chimpanzees), and domestic animals (for example, dogs and cats).

Any technique known in the art can be used to introduce transgenes into animals to produce the founder lines of transgenic animals. Such techniques include, but are not limited to, pronuclear microinjection (U.S. Pat. No. 4,873,191); retrovirus mediated gene transfer into germ lines (Van der Putten et al., *Proc. Natl. Acad. Sci., USA* 82:6148, 1985); gene targeting into embryonic stem cells (Thompson et al., *Cell* 56:313, 1989); and electroporation of embryos (Lo, *Mol. Cell. Biol.* 3:1803, 1983). Especially useful are the methods described in Yang et al. (*Proc. Natl. Acad. Sci. USA* 94:3004-3009, 1997).

For a review of techniques that can be used to generate and assess transgenic animals, skilled artisans can consult Gordon (*Intl. Rev. Cytol.* 115:171-229, 1989), and may obtain additional guidance from, for example: Hogan et al. Manipulating the Mouse Embryo, Cold Spring Harbor Press, Cold Spring Harbor, NY, 1986); Krimpenfort et al. (*Bio/Technology* 9:86, 1991), Palmiter et al. (*Cell* 41:343, 1985), Kraemer et al. (Genetic Manipulation of the Early Mammalian Embryo, Cold Spring Harbor Press, Cold Spring Harbor, NY, 1985), Hammer et al. (*Nature* 315:680, 1985), Purcel et al. (*Science*, 244:1281, 1986), Wagner et al. (U.S. Patent No. 5,175,385), and Krimpenfort et al. (U.S. Patent No. 5,175,384).

Methods for constructing a transgenic animal that develops liver cancer are also described below in the Examples section. A particularly useful transgenic animal is the IRS-1/*c-myc* double transgenic mouse described therein. Such transgenic animals are included within the present invention.

EXAMPLES

The invention is illustrated in part by the following examples, which are not to be taken as limiting the invention in any way.

Example 1. Functional Consequences of Frizzled-7 Receptor Overexpression in human Hepatocellular Carcinoma

HCC Tumors and Cell Lines

HCC tumor tissues were obtained from 30 males in Taiwan and South Africa.

5 Samples were obtained from sixteen individuals from Taiwan, all of whom had HBV-related disease. These sixteen individuals had undergone surgery for resection of tumor. There were fourteen samples from South African individuals who were 28 – 57 years old. Of these, ten had HBV-, one had HCV-, and two had hemochromatosis-related HCC. One individual's HCC was of unknown etiology.

10 There was a matched uninvolved nontumorous liver sample for all 30 HCC. Cirrhosis and/or fibrosis was present in 85%. Huh7, Focus, HepaRG¹⁹, Hep3B, and HepG2 hepatoma cell lines were grown in minimum essential medium Eagle (MEM) (Cellgro), and PLC/PRF/5 in DMEM (Cellgro), supplemented with 10% (vol/vol) fetal calf serum (FCS) (Sigma), 1X-MEM non-essential amino acid solution (Sigma), and 1% (vol/vol)

15 penicillin/streptomycin (Sigma).

Real-Time RT-PCR Assay

The copy number of *FZD7* mRNAs was quantified in unknown samples by measuring the *C_t* value followed by normalization to *18S* ribosomal RNA (18S rRNA)

20 after comparison to a standard curve for both *FZD7* and 18S rRNA. This ratio of *FZD7*/18S rRNA was subsequently normalized to a calibrator (mean value obtained from normal livers) and expressed as relative abundance of *FZD7* mRNA. Standards were prepared with 10-fold dilutions of the corresponding PCR products cloned into the pCR[®]2.1 Vector (Invitrogen, Life Technology). The specificity of the *FZD7* and *18S*

25 *rRNA* inserts was provided by sequence analysis. Serial dilution of *FZD7*- and *18S rRNA*-plasmids were aliquoted and stored at -20°C until use. Primers were selected using the Primer3 website (www-genome.wi.mit.edu/cgi-in/primer/primer3_www.cgi). Primers for *FZD7* and *18S rRNA* respectively (Invitrogen™ Life Technologies) were as follows: (a) *FZD7*, 5'-

30 GCCGCTTCTACCACAGACT-3' (SEQ ID NO:28; forward) and 5'-TTCATACCGCAGTCTCCCC-3' (SEQ ID NO:29; reverse) to yield a 54 bp amplicon; (b) human *18S rRNA*, 5'-GGACACGGACAGGATTGACA-3' (SEQ ID NO:30; forward) and 5'-ACCCACGGAATCGAGAAAGA-3' (SEQ ID NO:31; reverse) to give

a 50 bp amplicon. BLASTN searches were conducted against dbEST and nr (the nonredundant set of GenBank database sequences) to confirm the gene specificity of the nucleotide sequences chosen for the primers to confirm the lack of DNA polymorphism.

5 Total RNA was extracted from liver specimens and HCC cell lines by using TRIzol[®] reagent (Invitrogen, Life Technology). The quality of the RNA samples was determined by electrophoresis through agarose gels and staining with ethidium bromide; the 18S and 28S ribosomal RNA bands were visualized under UV light. A total amount of 250 ng total RNA was treated with DNase-I, RNase-free, and reverse
10 transcribed with random hexamers and the AMV reverse transcriptase, all from Roche Diagnostics Corporation (Indianapolis, USA). All PCR reactions were performed using an iCycler iQ[™] Multi-Color Real Time PCR Detection System (Bio-Rad, Hercules, USA) with a mix composed of 1X SYBR[®] Green PCR Master Mix (Applied Biosystems, USA), 500 nM each primer, and 5 ng cDNA (equivalent total RNA) from
15 unknown samples. The thermal cycling conditions comprised an initial step at 95°C for 10 minutes, followed by 40 cycles at 95°C for 15 seconds and 60°C for 1 minute. Experiments were performed in duplicate. Each PCR run included *FZD7* and *18S* standard curves, a non-template control, and the unknown cDNAs analyzed for *FZD7* and *18S rRNA* copy numbers.

20 Cell Motility Assay

 A luminescence-based assay was used to evaluate cell motility and migration. This assay assesses non-migrated, migrated-adherent, and migrated non-adherent hepatoma cells through uncoated polyvinylpyrrolidone-free polycarbonate filters as
25 previously described¹⁴ in chambers partitioned with 13 mm diameter, 8 µm pore polycarbonate membranes (Osmonics, Inc.). After 72 hours of growth in 1% FCS, cells were re-suspended in serum-free medium with soybean trypsin inhibitor (Sigma) at 0.5 mg per mL. In the lower chamber, collagen-I (Sigma) was diluted to 100 µg/mL in 200 µL of serum-free medium.⁸ After assembly of the chambers, 1×10^5 of the resuspended
30 cells were added to the upper chamber, and incubated for 3 hours in a CO₂ humidified incubator to allow cell migration to proceed. The cells remaining on the upper surface of the membrane (non-migrated) were harvested with a sterile cotton swab and placed into a well containing ATP lysis buffer (Packard Instrument Company, Meriden, CT).

To harvest migrated adherent cells, the membrane (devoid of non-migrated cells) was placed into another well containing ATP lysis buffer. The migrated non-adherent cells were harvested by re-suspending the cells in the lower compartment of the blind chamber and placing them into a third well containing ATP lysis buffer. ATPLite substrate was added to each well and luminescent counts per second were measured in a TopCount Microplate reader (Packard instrument Company). The results were analyzed using Excel (Microsoft Corp., Seattle, WA) to calculate percentages of non-migrated, migrated-adherent, and migrated non-adherent cells in each assay.

Transfection and Retroviral Transduction

Because the N-terminal ectodomain of Frizzled receptors functions as a natural antagonist of Frizzled-mediated signal transduction, a mutant cDNA with a C-terminal truncation (*FZD7-ΔTAC*) was generated as previously described.⁴⁴ The cDNA *FZD7-ΔTAC* cDNA was subcloned into a pcDNA3 mammalian expression vector (Invitrogen) and certified for protein expression by an *in vitro* translation reaction.⁴⁴ The *in vitro* effect of stable expression of *FZD7-ΔTAC* was examined in human hepatoma cells. The pcDNA3/ *FZD7-ΔTAC*, and pcDNA3/empty vectors were transfected by electroporation (250V voltage / 15 millisecond pulse with Gene Pulser II, BioRad). Stable transfectants were selected with 800 μg/ml Geneticin (Gibco) added to the culture medium. Expression of the *FZD7-ΔTAC* gene was assessed by quantitative real-time RT-PCR and Western blot analysis.

Two different *FZD7* truncated mutants either with deletions in the intracellular domain alone (*FZD7-ΔC*) or in both the intracellular and transmembrane domains (*FZD7-ΔTAC*) as well as a GFP control, were prepared by PCR using the Pfu-polymerase (Stratagene). Constructs were cloned into the lentiviral pLenti6/V5 Directional TOPO[®] vector (Invitrogen) downstream of the cytomegalovirus promoter. All constructs were verified by sequence analysis of both strands. Virions were produced in 293FT cells, and viral stocks were frozen at -80°C. Hepatoma cells were transduced at a MOI of 5, and stable clones were selected in the presence of blasticidin (4μg/mL). Quantitative real-time RT-PCR and Western blot analysis were used to detect gene expression. A mutant construct of β-catenin with biologic activity (ΔN/ΔC) was prepared by PCR using the Pfu-polymerase (Stratagene) as previously described² and following transfection, HCC

motility was assessed 72 hours later.

Transient transfection assays were performed to assess for Tcf transcriptional activity. In brief, cells were seeded in 6 well plates at a density of 3×10^5 cells/well the day prior to transfection. Transfections were performed with either TOPflash (Tcf Reporter Plasmid) or FOPflash (mutant Tcf binding sites) and β -galactosidase expressing plasmid in triplicate using Lipofectamine 2000 (Life Technologies, Inc., Rockville, MD). Focus, Huh7 and Hep3B cells were harvested 48 hours after transfection and luciferase activity was measured by a luminometer TopCount microplate reader (Packard Instrument Co.). Transfection efficiency was normalized by measurement of β -galactosidase activity. The experiment was performed three times.

Immunoprecipitation

Transfected cells were washed with cold phosphate-buffered saline, and pelleted at 2,000 rpm for 5 minutes and resuspended in 500 μ L of solubilization buffer (136 mM NaCl, 2.7 mM KCl, 12 mM Na_2HPO_4 , 1.8 mM KH_2PO_4 , pH 7.4, 1% NP-40 with protease inhibitors). Lysates were incubated for 3 hours at 4°C on a rocker platform and then microcentrifuged at 13,000 rpm for 15 minutes at 4°C to pellet-out cell debris. Lysates were immunoprecipitated in a 1.0-ml total volume with 500 μ L of lysate, 480 μ L of solubilization buffer, and 20 μ L of goat anti-human V5 antibodies coupled to agarose beads (Bethyl Laboratories, Inc.) for 12 hours at 4°C with constant shaking. The beads were washed twice with the solubilization buffer. Bound proteins were eluted by boiling for 5 minutes in SDS sample buffer. The proteins were separated on 10% polyacrylamide gel, transferred to PVDF membrane (NEN™ Life ScienceProducts, Boston, MA).

Protein Extraction and Western Blot Analysis

For whole protein extraction, hepatoma cells at 50% confluence were homogenized in lysis buffer [30 mM Tris (pH 7.5), 150 mM NaCl, 1% NP-40, 0.5% Na deoxycholate, 0.1% SDS, 10% glycerol, and 2 mM EDTA] with protease inhibitors (Roche Molecular Biochemicals) and sonicated. Protein concentration was determined with the BCA Protein Assay Kit (Pierce) using BSA as standard. Subcellular fractionations were performed as previously described.³³

Aliquots of proteins were resolved on SDS/PAGE and transferred onto PVDF membranes (NEN™ Life Science Products, Boston, MA) by electroblotting. The membranes were blocked with 5% nonfat dry milk in Tris-buffered saline containing 0.1% Tween 20 and then probed with a mouse monoclonal anti- β -catenin antibody diluted at 1:500 (Transduction Laboratories), or a mouse monoclonal anti-PCNA antibody diluted at 1:1,000 (Oncogene Science). A specific rabbit polyclonal antibody was prepared against a human FZD7 peptide QNTSDGSGGPGGGPTAYPTAPYLPD (SEQ ID NO:32), amino acids 163-187 (NCBI Protein database accession no. BAA_34668) and used at 1:5,000 dilution. Each primary antibody was followed by incubation with a secondary horseradish peroxidase antibody diluted 1:10,000 and then revealed with the chemiluminescence imaging Western Lightning (PerkinElmer™ Life Sciences, Boston, MA). The specificity of the antigen-antibody interaction was established by absorption of FZD7 immunoreactivity with specific and not with non-relevant peptides as well as lack of FZD7 protein detection with addition of second antibody alone (data not shown). All of the blots were standardized for equal protein loading by Ponceau S red staining.

Sequencing

PCR amplification of β -catenin exon-3, which contains the 4 potential sites for phosphorylation by GSK-3 β , was performed on the cDNAs derived from each tumor sample using a β -catenin exon-2 forward primer, and a β -catenin exon-4 reverse primer as previously described.³⁵ After resolution of the PCR products by 2% agarose gel electrophoresis and visualization with ethidium bromide, PCR products were excised and cloned into the pCR®2.1 Vector (Invitrogen, Life Technology). Sequencing was performed in both directions using T7 forward and M13 reverse primers.

Statistical Analysis

The dependent or independent *t*-tests were used for continuous data with StatView Software Version 5.0 (SAS Institute Inc.). Tests were considered significant when their P values were < 0.05.

Real-Time RT-PCR Assay for FZD7

Random hexamers were used for the initial reverse transcription step. The amplification was performed with set of primers generating a small amplicon size (around 50 bp) for both *FZD7* and *18S rRNA*. Fig. 1 shows the standard curves for the *FZD7* and *18S rRNA* and illustrates the values obtained for unknown tumor samples. A linear relationship between the C_t and the log of the starting copy number was demonstrated ($R_2 \geq 0.99$). The efficiency of the reaction (E), calculated by the formula: $E = 10_{1/m} - 1$, where m is the slope of the standard curve,⁴ ranged from 90 to 100% in the assays performed at different times. The same features with respect to the dynamic range and efficiency of the reactions were observed with serial dilutions of cDNAs derived from the Huh7 cell line, or from human HCC tumors when using 10 to 0.625 ng of equivalent total RNA (data not shown). Sensitivity was < 10 copies per reaction for *FZD7* and 100 copies for *18S rRNA*.

FZD7 gene expression was measured in HepG2, Hep3B, HepaRG, PLC/PRF/5, Focus, and Huh7; values obtained on four normal adult liver tissues served as a controls and the mean value of these normal livers served as a calibrator for normalization of *FZD7* mRNA levels in other unknown samples. All cell lines were found to express *FZD7* mRNA gene at higher levels than normal liver (Fig. 1C). Huh7, PLC/PRF/5, and Focus cells exhibited the highest levels of *FZD7* mRNA with ratios of 354, 116, and 8, respectively, compared to normal livers. In contrast, Hep3B, HepaRG, and HepG2 had lower levels of expression with ratios of 15, 11, and 9 respectively.

Correlation of Steady State *FZD7* mRNA Levels and HCC Motility

Because the Wnt-Frizzled signal transduction pathway is involved in cell motility and migration,⁴⁶ motility of HepG2, Hep3B, Focus, and Huh7 cells in the context of *FZD7* gene expression was examined. Fetal calf serum was not used as chemoattractant⁴⁴ since serum growth factors may interfere with β -catenin stabilization independent of the Wnt-Frizzled signals.^{34,43} Under the experimental conditions of using soluble collagen-I as a chemoattractant, a significant correlation between *FZD7* steady state mRNA levels and percent of total migrated cells (both adherent and nonadherent) was observed (Figs. 2A and 2B). The highest *FZD7* mRNA levels and motility rates were found in Huh7 cells.

Subcellular Localization of β -catenin

To explore the hypothesis that Wnt-Frizzled signal may act through the canonical β -catenin pathway to control cellular motility, the β -catenin status in HCC cell lines was evaluated. It was found that Huh7, Focus, and Hep3B cells have a homozygous wild-type β -catenin as described previously.⁵ HepG2 cells have a heterozygous deletion in exon-3 and make both wildtype and mutant β -catenin proteins.⁹ β -catenin may be bound to either the cytosolic GSK3 β /Axin/APC complex or membrane-linked with E-cadherin or c-Met.³⁴ Upon signaling by Wnt through its Frizzled receptor and subsequent interaction with dishevelled, the GSK3 β /Axin/APC/ β -catenin complex undergoes dephosphorylation causing β -catenin dissociation from the complex, followed by its nuclear translocation. Thus nuclear versus cytosolic localization of wild-type β -catenin was explored in these HCC cell lines. The β -catenin protein levels are shown in Figure 3A. It was of interest that two HCC cell lines namely Huh7 and Focus with the highest *FZD7* gene expression, had a striking nuclear subcellular localization of wild-type β -catenin (Fig. 3B). Furthermore, the levels of *FZD7* mRNA appear to not correlate with the cellular proliferation index as assessed by levels of proliferating cell nuclear antigen (*PCNA*) (Fig. 3A).

In addition, Huh7, Focus and Hep3B showed high basal Tcf transcriptional activity and there was a general correlation between the level of Tcf transcriptional activity and *FZD7* receptor expression (Fig. 3C). These results are also consistent with the levels of β -catenin found within the cell and its nuclear localization. These findings suggest that activation of the canonical Wnt/ β -catenin pathway is involved in the multi-step process of hepatocyte transformation.

Expression of a Dominant-Negative *FZD7* Receptor Mutants Inhibits Wild-Type – Catenin Accumulation and Motility of HCC Cells

The motility and accumulation of wild-type β -catenin was assessed in human HCC cell lines after down-regulation of the *Wnt-FZD7* signal following ectopic expression of two types of dominant negative *FZD7* mutant receptors: 1) The *FZD7- Δ T- Δ C* represents a secreted *FZD7* receptor where both intracellular and transmembrane domains have been truncated; this construct inhibits Wnt signaling in human esophageal carcinoma cell lines,⁴⁴ and 2) the *FZD7- Δ C* construct where the transmembrane *FZD7* receptor has been truncated in the intracellular domain only as

depicted in Figure 4A. Since *FZD7-ΔTAC* receptor acts as a soluble Wnt ligand binding protein, studies were performed on a heterogeneous population of stably transfected cells. HCC cells were selected in the presence of geneticin and subsequently evaluated for motility and accumulation of wild-type β -catenin. The *FZD7-ΔC* mutant receptor
5 does not act as a soluble ligand but is closely linked to the membrane with its 7 transmembrane domains. The *FZD7-ΔC* cDNA was cloned into the lentiviral vector pLenti6/V5-D-TOPO[®] to allow for a high transduction efficiency in both dividing and non-dividing cells. Preliminary experiments with a similarly cloned GFP construct indicated that
10 over 80% of human HCC cells will abundantly express GFP from 72 hr to 3 weeks post-transduction. Ectopic expression of *FZD7-ΔC* and *FZD7-ΔTAC* was assessed by Western blot and quantitative real-time RT-PCR using different set of primers targeting specifically either the extracellular or the intracellular domain of *FZD7*, allowing to differentially assess the ectopic expression of *FZD7-ΔC* and *FZD7-ΔTAC* by
15 comparison to the endogenous expression of the wild-type full-length *FZD7* receptor (Figs. 4B, 4C, 4D, and 4E).

The secreted *FZD7-ΔTAC* ectodomain is a functional antagonist of endogenous *FZD7* signaling by suppression of the interaction of APC with β -catenin in the KYSE150 esophageal carcinoma cell line.⁴⁴ Results herein demonstrate that ectopic
20 expression of *FZD7-ΔTAC* or *FZD7-ΔC* causes a decrease of β -catenin protein levels in all HCC cell lines with a homozygous wild-type β -catenin gene presumably through down-regulation of the Wnt-*FZD7* signal transduction cascade (Figs. 5A and 5B). In contrast, β -catenin mRNA steady state levels were not altered by transfection of the dominant negative mutant constructs as assessed by real-time RT-PCR (data not
25 shown). However, no effects of these mutant receptor constructs were observed on β -catenin levels in HepG2 cells which have a heterozygous β -catenin deletion (Fig. 5A).

If *FZD7* is potentially involved in cellular motility via the canonical β -catenin pathway, it became important to evaluate the impact of down-regulation of the Wnt-*FZD7* signal on motility of Huh7 cells.³⁵ Results herein demonstrate that ectopic
30 expression of the transmembrane anchored *FZD7-ΔC* mutant receptor was very effective in reducing the number of motile Huh7 cells under conditions of transient expression as shown in Fig. 5C. In addition, this construct was more efficient in

reducing motility than the secreted *FZD7-ΔTAC* mutant receptor. These observations were further confirmed by striking inhibitory effects on cell motility by two independent stable clones expressing either *FZD7-ΔC* at high levels (*FZD7-ΔC-C5*, and *FZD7-ΔC-C6* respectively), compared to a *FZD7-ΔTAC* expressing clonal cell line
 5 (*FZD7-ΔTAC-C1*) as shown in Fig. 5D.

In order to establish a clear link between regulation of the canonical Wnt/β-catenin pathway and the *FZD7*-mediated alteration of cell motility in Huh7 cells, experiments were performed to restore cell motility by ectopic expression of a mutant β-catenin construct in Huh7 cells harboring a low motility phenotype due to
 10 overexpression of a dominant-negative *FZD7* receptor mutant protein. A pLenti6/V5-D-TOPO[®] lentiviral vector expressing the ΔN/ΔC β-catenin mutant was generated (Figure 6A) that had been previously shown to exhibit transactivating properties on Lef/Tcf regulated target genes in HEK cells.² The *FZD7-ΔC-C6* and *GFP-C4* blasticidin-selected clonal Huh7 cell populations were co-transduced by the ΔN/ΔC β-catenin mutant lentivirus construct or *GFP* as a control to keep constant the total
 15 amounts of plasmid DNA within Huh7 cells. In this context, the motility of co-transduced Huh7 cells was assessed and demonstrated that the low motility phenotype induced by stable *FZD7-ΔC* expression could be reversed by ectopic expression of the ΔN/ΔC mutant β-catenin protein (Fig. 6B). These experiments further support a role
 20 for activation of the canonical Wnt/β-catenin pathway during hepatic oncogenesis in cells overexpressing *FZD7* receptors.

***FZD7* mRNA is Overexpressed in Human HCC Tumors**

Normal liver showed low *FZD7* mRNA expression (Fig. 7A and Table 1,
 25 below). Among 30 paired samples tested from two regions of the world, 27 (90%) displayed significant *FZD7* overexpression in comparison to corresponding peritumorous areas (non-parametric paired test, $p < 0.0001$; paired t -test, $p = 0.0187$) (Fig. 7A). These findings were confirmed at the protein level by Western blot analysis (Fig. 7B). Results were similar between tumors derived from South Africa, and Taiwan
 30 with an average increase of 12 fold between tumor and peritumorous areas. High levels of *FZD7* mRNAs as defined by a value above the cut-off (mean of normal liver ± 3 SD, $\alpha = 0.01$) were observed in 29 tumors (97%), and 23 peritumoral areas (77%) compared to completely normal adult liver controls. These observations led us to

believe that *FZD7* mRNA up-regulation may be an early event occurring in the preneoplastic peritumorous area of the liver.

Similar to the *in vitro* observations in HCC cell lines, β -catenin levels in comparison to *FZD7* gene expression was explored in human tumors. It was found that, among 5 different HCC expressing *FZD7* mRNA at >100-fold above the mean of normal livers, 4 of the 5 HCC were associated with a homozygous wild-type β -catenin exon-3 gene. However, one tumor (HCC #28) had a heterozygous deletion of one β -catenin allele similar to that found in the HepG2 cell line. Western blot analysis of cytosolic and nuclear enriched fractions demonstrated that wild-type β -catenin protein also accumulates in HCC and peritumorous areas in the context of elevated *FZD7* mRNA expression and in the absence of β -catenin exon-3 mutations as shown in Fig. 7C. The findings in human tumors, therefore, confirm our *in vitro* observations in HCC cell lines.

Discussion

The data herein provide direct evidence by real-time RT-PCR that *FZD7* receptor gene expression is commonly up-regulated in an early event during the development of HCC. A rabbit polyclonal antibody to a unique peptide of *FZD7* was developed to confirm that this receptor is also up-regulated at the protein level as well by Western blot analysis. The biologic consequences of this event are the stabilization of wild-type β -catenin and enhanced tumor cell migration.

Activation of cellular oncogenes (i.e., *c-myc*),⁴⁹ growth factors (i.e., insulin-like growth factor II and transforming growth factor type α)^{7,15,48} in association with mutations of tumor suppressor genes (i.e., *P53*, *RB*, and *IGF1R*)^{15,23,50} have been described in human and animal models of HCC. However, these genetic events are present in <50% of HCC tumors and usually occur late in the multistep process of hepatocarcinogenesis and not in precancerous lesions of dysplasia, cirrhosis, and non-cirrhotic chronic hepatitis. More recently, aberrant accumulation of the potential oncogenic β -catenin protein, due to mutations of the gene has been found in both human and murine HCC tumors but such mutations are unusual (15% of HCCs) and of late occurrence since they are absent in dysplasia, cirrhosis or liver fibrosis.^{13,16}

Additional studies have revealed that in 35-80% of HCC, aberrant accumulation of β -catenin is not associated with mutations of β -catenin, Axin1 or APC genes of this

Wnt inducible signal transduction pathway.^{12, 17,24, 30,47} Although p53 gene mutations could contribute, in part, to aberrant accumulation of wild-type β -catenin, the frequency of gene mutations is relatively low. The level of nuclear and cytoplasmic β -catenin accumulation in such tumors therefore remains unexplained.⁵ The possibility that other members of the *Wnt*/ β -catenin signal transduction pathway could contribute to aberrant accumulation of wild-type β -catenin in HCC cells was explored. During initiation of the *Wnt* signaling cascade, binding of a *Wnt* ligand to its target, the Frizzled receptor, may lead either to the stabilization of intracellular β -catenin protein²⁰ or activation of downstream molecules such as c-Jun NH₂-terminal kinase (JNK) and protein kinase C.²⁹ However, if Frizzled receptors were overexpressed, this signal transduction pathway might be constitutively activated. Human HCC cell lines, as well as tumors were evaluated, and the biologic consequences of *FZD7* overexpression were assessed.

All HCC cell lines were found to overexpress the *FZD7* gene at different levels. Indeed analysis of human liver tumors showed frequent *FZD7* gene up-regulation as compared with normal liver, and adjacent uninvolved areas. The general finding of significant overexpression in “pre-neoplastic” peritumoral tissue as compared to normal liver suggests that up-regulation of this gene may be an early event in hepatocarcinogenesis. Once complete transformation has occurred, higher levels of *FZD7* were observed. These results suggest that activation of the the *Wnt*/ β -catenin signaling due to *FZD7* receptor overexpression alone or possibly in association with LRP-coreceptor and *Wnt* ligand expression or overexpression, may be one of the major early events of the stepwise process leading to hepatocyte transformation.

Activation of the canonical *Wnt* pathway results in accumulation of the free β -catenin pool in the cytoplasm. After forming a transcriptional transactivator complex with Tcf/Lef, β -catenin translocates to the nucleus.²⁰ Subsequently, transactivation of genes involved in cell migration will occur. It was found that high levels of *FZD7* mRNA expression were almost exclusively associated with nuclear and/or cytoplasmic accumulation of β -catenin in HCC lines and human tumors with the wild type gene. However, as an exception, up-regulation of *FZD7* gene expression was observed in the context of a heterozygous β -catenin exon-3 gene deletion in one HCC tumor (HCC #28) and cell line (HepG2). It is possible that an internal deletion of the β -catenin gene

abolishes phosphorylation sites (localized within exon-3) and abrogates the canonical Wnt-Frizzled signaling *via* the mutated β -catenin allele.³⁷ In this setting, *FZD7* may signal through either (a) the canonical β -catenin pathway *via* the wild-type β -catenin allele or (b) the non-canonical β -catenin-independent pathway involving the activation of protein kinase C (PKC).²⁹ Down-regulation of the *Wnt-FZD7* signaling by ectopic expression of different dominant negative mutants of *FZD7* receptors (i.e., the transmembrane *FZD7-ΔC*, or the secreted *FZD7-ΔTΔC*) is associated with markedly reduced accumulation of β -catenin protein in the cytoplasm and nucleus of HCC cell lines that display a homozygous wild-type β -catenin gene. However, the observed inefficiency of dominant negative mutant *FZD7* receptors for reducing accumulation of the wild-type β -catenin protein in the environment of a heterozygous β -catenin-mutation, as was shown in HepG2 cells, emphasizes the potential cooperation between non-canonical and β -catenin independent pathways for mediating the *Wnt-FZD7* signaling.

The Wnt/Frizzled signaling network influences diverse biological processes.²⁸ The β -catenin protein belongs to a family of structural proteins that includes catenins and cadherins. By forming a membrane associated complex, these proteins mediate adhesion and are essential for the processes of cellular motility and migration.^{32,35} Therefore, the role of *FZD7* gene expression in HCC cell motility was investigated. An ATP luminescence-based assay was used to quantify directional cell motility values in chemotaxis chambers and we observed that the magnitude of that steady state *FZD7* mRNA levels were strongly correlated with enhanced motility of HCC cells. To further characterize the role of *Wnt-FZD7* signal on cell motility, experiments demonstrated that interfering with the Wnt-FZD7 interaction by ectopic expression of dominant negative mutant *FZD7* receptors led to marked reduction of HCC cell migration and occurred in the context of a homozygous wild-type β -catenin gene. These results support previous findings on the inhibitory effect of natural secreted Frizzled-related proteins on the motility of human glioma cells.⁴¹ Of interest was the observation that the transmembrane *FZD7-ΔC* mutant receptor was more effective than the secreted *FZD7-ΔTΔC* soluble receptor with respect to inhibiting Huh7 cell motility and migration. It is likely that Huh7 cells can secrete yet unidentified Wnt ligand for binding to the *FZD7*

receptor. The secreted *FZD7-ΔTAC* mutant receptor may be less efficient in binding, or could be overwhelmed by the high number of secreted Wnt ligand molecules. In contrast, the transmembrane *FZD7-ΔC* mutant receptor may be saturated and efficient since it has the capability to bind to the LRP5 co-receptor to allow for optimal transmission of the Wnt signal. Finally, the experiments suggest that the canonical β-catenin pathway may be involved in the *FZD7*-mediated regulation of Huh7 cell motility. Indeed, it has been observed that ectopic expression of a β-catenin mutant was able to restore high levels of motility in Huh7 cells where the Wnt/β-catenin mediated signal transduction cascade has been inhibited at the receptor level by stable expression of a dominant negative *FZD7-ΔC* construct.

In summary, deregulation of the Wnt-APC-β-catenin pathway is found in a number of human (colorectal, lung, breast, cervix, melanoma, and HCC) tumors.^{6,11,22,26,27,31,38,40,45} Most reports have established that this deregulation may be due to β-catenin gene mutation.¹³ This study shows for the first time that over 90% of human HCC have up-regulation of the *FZD7* receptor gene and this phenomenon was functionally associated with stabilization of wild-type β-catenin and enhanced HCC cell motility. Therefore, enhanced *FZD7* gene expression is the most common and one of the earliest genetic abnormality observed thus far in HCC and is probably responsible for the β-catenin accumulation in human HCC tumors without β-catenin, axin or APC mutations. Molecular mechanisms that may lead to up-regulation of *FZD7* gene may include 1) paracrine or autocrine induction by Wnt ligands, 2) gene amplification and 3) demethylation of *FZD7* gene promoter sequences.

Although the present study emphasized the canonical Wnt/β-catenin signaling pathway, Wnt/Frizzled signals may activate at least two other intracellular signaling pathways including the planar cell polarity pathway that signals through the small GTPase Rho, and another signaling cascade that activates isoforms of protein kinase C.^{10,46} These pathways may play a role in the context of a homozygous wild-type β-catenin gene or in tumors with β-catenin mutations and deletions.

Geographic Area	HCC Sample #	T Etiology	T [FZD7 mRNA levels]	pT [FZD7 mRNA levels]	Ratio T/pT
Taiwan	1	HBV	18.5	7.3	2.5
	2	HBV	46.5	6.9	6.7
	3	HBV	11.6	5.8	2.0
	4	HBV	53.1	7.6	7.0
	5	HBV	60.7	9.5	6.4
	6	HBV	16.0	3.3	4.8
	7	HBV	31.3	14.2	2.2
	8	HBV	17.1	18.5	0.9
	9	HBV	9.5	13.1	0.7
	10	HBV	19.6	6.5	3.0
	11	HBV	134.2	19.6	6.8
	12	HBV	657.1	10.2	64.4
	13	HBV	38.2	18.5	2.1
	14	HBV	9.5	3.6	2.6
	15	HBV	84.0	30.9	2.7
	16	HBV	38.2	6.9	5.5
South Africa	17	HBV	442.9	33.5	13.2
	18	HBV	8.4	0.7	12.0
	19	HBV	4.0	0.4	10.0
	20	Hemochromatosis	0.7	4.4	0.2
	21	HBV	33.5	6.2	5.4
	22	HBV	31.3	10.2	3.1
	23	HBV	4.7	1.1	4.3
	24	HBV	7.3	0.4	18.3
	25	HCV	29.1	3.3	8.8
	26	HBV	14.9	2.2	6.8
	27	HBV	33.1	4.7	7.0
	28	Unknown	296.4	2.2	134.7
	29	Hemochromatosis	14.9	8.4	1.8
	30	HBV	20.7	1.8	11.5
Normal Liver		Normal Liver			
Taiwan	31		0.4		
	32		0.7		
So. Africa	33		1.8		
	34		1.1		

Table 1: *FZD7* mRNA steady state levels assessed by quantitative real-time RT-PCR in paired samples including HCC tumor (T) *versus* the corresponding peritumorous liver (pT).

REFERENCES

1. Aberle, H., Schwartz, H., and Kemler, R. 1996. Cadherin-catenin complex: protein interactions and their implications for cadherin function. *J. Cell. Biochem.*, **61**:514-523.
2. Aoki, M., Sobek, V., Maslyar, D., Hecht, A., and Vogt, P.K. 2002. Oncogenic transformation by β -catenin: deletion analysis and characterization of selected target genes. *Oncogene*, **21**:6983-6991.
3. Bhanot, P., Brink, M., Samos, C.H., Hsieh, J.C., Wang, Y., Macke, J.P., Andrew, D., Nathans, J., and Nusse, R. 1996. A new member of the frizzled family from *Drosophila* functions as a Wingless receptor. *Nature*, **6588**:225-230.
4. Bieche, I., Laurendeau, I., Tozlu, S., Olivi, M., Vidaud, D., Lidereau, R., and Vidaud, M. 1999. Quantitation of *MYC* gene expression in sporadic breast tumors with a real-time reverse transcription-PCR assay. *Cancer Res.* **59**:2759-2765.
5. Cagatay, T., and Ozturk, M. 2002. P53 mutation as a source of aberrant β -catenin accumulation in cancer cells. *Oncogene*, **21**:7971-7980.
6. Candidus, S., Bischoff, P., Becker, K.F., and Hofler, H. 1996. No evidence for mutations in the alpha- and beta-catenin genes in human gastric and breast carcinomas. *Cancer Res.*, **56**:49-52.
7. Cariani, E., Lasserre, C., Seurin, D., Hamelin, B., Kemeny, F., Franco, D., Czech, M.P., Ullrich, A., and Brechot, C. 1988. Differential expression of insulin-like growth factor II mRNA in human primary liver cancers, benign liver tumors, and liver cirrhosis. *Cancer Res.*, **48**:6844-6849.

8. Carloni, V., Mazzocca, A., Pantaleo, P., Cordella, C., Laffi, G., and Gentilini, P. 2001. The integrin, $\alpha 6 \beta 1$, is necessary for the matrix-dependent activation of FAK and MAP kinase and the migration of human hepatocarcinoma cells. *Hepatology*, 34:42-49.
9. Carruba, G., Cervello, M., Micell, M.D., Farruggio, R., Notarbartolo, M., Virruso, L., Giannitrapani, L., Gambino, R., Montalto, G., Castagnetta, L. 1999. Truncated form of b-catenin and reduced expression of wild-type catenins feature HepG2 human liver cancer cells. *New York Acad. Sci.*, 886:212-216.
10. Cheon, S.S., Cheah, A.Y., Turley, S., Nadesan, P., Poon, R., Clevers, H., and Alman, B.A. 2002. β -catenin stabilization dysregulates mesenchymal cell proliferation, motility, and invasiveness and causes aggressive fibromatosis and hyperplastic cutaneous wounds. *Proc. Natl. Acad. Sci. U S A*, 10:6973-6978.
11. Chung, D.C. 2000. The genetic basis of colorectal cancer: insights into critical pathways of tumorigenesis. *Gastroenterology*, 119:854-865.
12. Clevers, H. Axin and hepatocellular carcinomas. 2000. *Nat. Genet.*, 24:206-208.
13. de la Coste, A., Romagnolo, B., Billuart, P., Renard, C.A., Buendia, M.A., Soubrane, O., Fabre, M., Chelly, J., Beldjord C., Kahn, A., and Perret, C. 1998. Somatic mutations of the β -catenin gene are frequent in mouse and human hepatocellular carcinoma. *Proc. Natl. Acad. Sci. USA*, 95:8847-8851.
14. de la Monte, S.M., Lahousse, S.A., Carter, J., and Wands, J.R. 2002. ATP luminescence-based motility-invasion assay. *Biotechniques*. 33:98-100.
15. de Souza, A.T., Hankins, G.R., Washington, M.K., Orton, T.C., and Jirtle, R.L. 1995. M6P/IGF2R gene is mutated in human hepatocellular carcinomas with loss of heterozygosity. *Nat. Genet.*, 11:447-449.

16. Devereux, T.R., Anna, C.H., Foley, J.F., White, C.M., Sills, R.C., and Barrett, J.C. 1999. Mutation of beta-catenin is an early event in chemically induced mouse hepatocellular carcinogenesis. *Oncogene*, 18:4726-4733.
17. Devereux, T.R., Stern, M.C., Flake, G.P., Yu, M.C., Zhang, Z.Q., London, S.J., and Taylor, J.A. 2001. CTNNB1 mutations and beta-catenin protein accumulation in human hepatocellular carcinomas associated with high exposure to aflatoxin B1. *Mol. Carcinog.*, 31:68-73.
18. Feitelson, M.A., Sun, B., Tufan, N. L. S., Liu, J., Pan, J., and Lian, Z. 2002. Genetic mechanisms of hepatocarcinogenesis. *Oncogene*, 21:2593-2604.
19. Gripon, P., Rumin, S., Urban, S., Le Seyec, J., Glaise, D., Canie, I., Guyomard, C., Lucas, J., Trepo, C., and Guguen-Guillouzo, C. 2002. Infection of a human hepatoma cell line by hepatitis B virus. *Proc. Natl. Acad. Sci. U S A*, 24:15655-15660.
20. He, T.C., Sparks, A.B., Rago, C., Hermeking, H., Zawel, L., Da Costa, L.T., Morin, P.J., Vogelstein, B., and Kinzler, K.W. 1998. Identification of c-MYC as a target of the APC pathway. *Science*, 5382:1438-1441.
21. Holcombe, R.F., Marsh, J.L., Waterman, M.L., Lin, F., Milovanovic, T., and Truong, T. 2002. Expression of Wnt ligands and Frizzled receptors in colonic mucosa and in colon carcinoma. *Mol. Pathol.*, 55:220-226.
22. Hommura, F., Furuuchi, K., Yamazaki, K., Ogura, S., Kinoshita, I., Shimizu, M., Moriuchi, T., Katoh, H., Nishimura, M., and Dosaka-Akita, H. 2002. Increased expression of beta-catenin predicts better prognosis in non-small cell lung carcinomas. *Cancer*, 94:752-758.
23. Hsu, I.C., Metcalf, R.A., Sun, T., Welsh, J.A., Wang, N.J., and Harris, C.C. 1991. Mutational hotspot in the p53 gene in human hepatocellular carcinomas. *Nature*, 350:427-428.

24. Hsu, H.C., Jeng, Y.M., Mao, T.L., Chu, J.S., Lai, P.L., and Peng, S.Y. 2000. β -catenin mutations are associated with a subset of low-stage hepatocellular carcinoma negative for hepatitis B virus and with favorable prognosis. *Am. J. Pathol.*, **157**:763-770.
25. Huang, H., Fuji, H., Sankila, A., Mahler-Araujo, B.M., Matsuda, M., Cathomas, G., and Ohgaki, H. 1999. β -catenin mutations are frequent in human hepatocellular carcinomas associated with hepatitis C virus infection. *Am. J. Pathol.*, **155**:1795-1801.
26. Inagawa, S., Itabashi, M., Adachi, S., Kawamoto, T., Hori, M., Shimazaki, J., Yoshimi, F., and Fukao, K. 2002. Expression and prognostic roles of β -catenin in hepatocellular carcinoma: correlation with tumor progression and postoperative survival. *Clin. Cancer Res.*, **8**:450-456.
27. Johnsson, M., Borg, A., Nilbert, M., and Andersson, T. 2000. Comments on involvement of adenomatous polyposis coli (APC) β -catenin signaling in human breast cancer, *Eur. J. Cancer*, **36**:242-248.
28. Jones, S.E., and Jomary, C. 2002. Secreted Frizzled-related proteins: searching for relationships and patterns. *BioEssays*, **24**:811-820.
29. Kuhl, M., Sheldahl, L.C., Park, M., Miller, J.R., and Moon, R.T. 2000. The Wnt/ Ca^{2+} pathway. A new vertebrate Wnt signaling pathway takes shape. *Trends Genet.*, **16**:279-283.
30. Laurent-Puig, P., Legoix, P., Bluteau, O., Belghiti, J., Franco, D., Binot, F., Mones, G., Thomas, G., Bioulac-Sage, P., and Zucman-Rossi, J. 2001. Genetic alterations associated with hepatocellular carcinomas define distinct pathways of hepatocarcinogenesis. *Gastroenterology*, **120**:1763-1773.

31. Lin, S.Y., Xia, W., Wang, J.C., Kwong, K.Y., Spohn, B., Wen, Y., Pestell, R.G., and Hung, M.C. 2000. β -catenin, a novel prognostic marker for breast cancer: its roles in cyclin D1 expression and cancer progression. *Proc. Natl. Acad. Sci. USA.*, 7:4262-4266.
32. Liu, D., el-Hariry, I., Karayiannakis, A.J., Wilding, J., Chinery, R., Kmiot, W., McCrea, P.D., Gullick, W.J., and Pignatelli, M. 1997. Phosphorylation of β -catenin and epidermal growth factor receptor by intestinal trefoil factor. *Lab. Invest.*, 6:557-563.
33. Maloney, J.A., Tsygankova, O., Szot, A., Yang, L., Li, Q., and Williamson, J.R. 1998. Differential translocation of protein kinase C isozymes by phorbol esters, EGF, and ANG II in rat liver WB cells. *Cell Physiol.* 274:974-982.
34. Monga, S.P.S., Mars, W.M., Pediaditakis, P., Bell, A., Mule, K., Bowen, W.C., Wang, X., Zarnegar, R., and Michalopoulos, G.K. 2002. Hepatocyte growth factor induces Wnt-independent nuclear translocation of β -catenin after Met- β -catenin dissociation in hepatocytes. *Cancer Res.*, 62:2064-2071.
35. Muller, T., Choidas, A., Reichmann, E., and Ullrich, A. 1999. Phosphorylation and free pool of beta-catenin are regulated by tyrosine kinases and tyrosine phosphatases during epithelial cell migration. *J. Biol. Chem.*, 15:10173-10183.
36. Nhieu, J.T., Renard, C.A., Wei, Y., Cherqui, D., Zafrani, E.S., and Buendia M.A. 1999. Nuclear accumulation of mutated β -catenin in hepatocellular carcinoma is associated with increased cell proliferation. *Am. J. Pathol.*, 155:703-710.
37. Noort, M.V., Meeldijk, J., van der Zee, R., Destree, O., and Clevers, H. 2002. Wnt signaling controls the phosphorylation status of β -catenin. *J. Biol. Chem.*, 20:17901-17905.

38. Park, W.S., Oh, R.R., Park, J.Y., Kim, P.J., Shin, M.S., Lee, J.H., Kim, H.S., Lee, S.H., Kim, S.Y., Park, Y.G., et al. 2001. Nuclear localization of β -catenin is an important prognostic factor in hepatoblastoma. *J. Pathol.*, **193**:483-490.
39. Polakis, P. 1997. The adenomatous polyposis coli (APC) tumor suppressor. *Biochim. Biophys. Acta.*, **1332**:F127-147.
40. Rimm, D.L., Caca, K., Hu, G., Harrison, F.B., and Fearon, E.R. 1999. Frequent nuclear/cytoplasmic localization of β -catenin without exon 3 mutations in malignant melanoma. *Am. J. Pathol.*, **154**:325-329.
41. Roth, W., Wild-Bode, C., Platten, M., Grimmel, C., Melkonyan, H.S., Dichgans, J., and Weller, M. 2000. Secreted Frizzled-related proteins inhibit motility and promote growth of human malignant glioma cells. *Oncogene*, **37**:4210-4220.
42. Satoh, S., Daigo, Y., Furukawa, Y., Kato, T., Miwa, N., Nishiwaki, T., Kawasoe, T., Ishiguro, H., Fujita, M., Tokino, T., et al. 2000. AXIN1 mutations in hepatocellular carcinomas, and growth suppression in cancer cells by virus-mediated transfer of AXIN1. *Nat. Genet.*, **24**:245-250.
43. Satyamoorthy, K., Li, G., Vaidya, B., Patel, D., and Herlyn, M. 2001. Insulin-like growth factor-1 induces survival and growth of biologically early melanoma cells through both the mitogen-activated protein kinase and β -catenin pathways. *Cancer Res.*, **61**:7318-7324.
44. Tanaka, S., Akiyoshi, T., Mori, M., Wands, J.R., and Sugimachi, K. 1998. A novel frizzled gene identified in human esophageal carcinoma mediates APC/ β -catenin signals. *Proc. Natl. Acad. Sci. USA*. **95**:10164-10169.

45. Ueda, M., Gemmill, R.M., Wset, J., Winn, R., Sugita, M., Tanaka, M., Ueki, M., and Drabkin, H.A. 2001. Mutations of the beta- and gamma-catenin genes are uncommon in human lung, breast, kidney, cervical and ovarian carcinomas. *Br. J. Cancer*, 85:64-68.
46. Weeraratna, A.T., Jiang, Y., Hostetter, G., Rosenblatt, K., Duray, P., Bittner, M., and Trent, J.M. 2002. Wnt5a signaling directly affects cell motility and invasion of metastatic melanoma. *Cancer Cell*, 3:279-288.
47. Wong, C.M., Fan, S.T., and Ng, I.O. 2001. β -catenin mutation and overexpression in hepatocellular carcinoma: clinicopathologic and prognostic significance. *Cancer*, 92:136-145.
48. Yeh, Y.C., Tsai, J.F., Chuang, L.Y., Yeh, H.W., Tsai, J.H., Florine, D.L., and Tam, J.P. 1987. Elevation of transforming growth factor alpha and its relationship to the epidermal growth factor and alpha-fetoprotein levels in patients with hepatocellular carcinoma.. *Cancer Res.*, 47:896-901.
49. Zhang, X.K., Huang, D.P., Qiu, D.K., and Chiu, J.F. 1990. The expression of c-myc and c-N-ras in human cirrhotic livers, hepatocellular carcinomas and liver tissue surrounding the tumors. *Oncogene*, 5:909-914.
50. Zhang, X., Xu, H.J., Murakami, Y., Sachse, R., Yashima, K., Hirohashi, S., Hu, S.X., Benedict, W.F., and Sekiya, T. 1994. Deletions of chromosome 13q, mutations in Retinoblastoma 1, and retinoblastoma protein state in human hepatocellular carcinoma. *Cancer Res.*, 54:4177-4182.

Example 2. Oncogenic Role of the Frizzled-7/ β -catenin Pathway in Hepatocellular Carcinoma

INTRODUCTION

Hepatocellular carcinoma (HCC) is one of the most frequent fatal malignancies worldwide.¹ It occurs at a high rate in Asia and Africa² and has been gradually increasing in Western countries as well.^{3, 4} Although major environmental risks have been identified such as chronic hepatitis B and C virus infection, exposure to aflatoxin B1, alcohol consumption and anabolic steroids, the molecular mechanisms of hepatocarcinogenesis remain largely unknown.^{5, 6} Activation of cellular oncogenes (*c-myc*)⁷, growth factors (insulin-like growth factor II and transforming growth factor type α)^{8, 9, 10} in association with mutations of tumor suppressor genes (*P53*, *RB*, and *IGF1R*)^{8, 11, 12} have been described in human and animal models of HCC. In addition, loss of heterozygosity (LOH) at chromosomes 1p, 4q, 6q, 8p, 9p, 16p, 16q, and 17p has also been identified at high frequency in HCC and suggest that several genes are involved in the multistep process of hepatocarcinogenesis.^{5, 13}

More recently, the observation of aberrant activation of the Wnt/ β -catenin pathway as manifested by cellular and nuclear accumulation of this protein due to mutations of the β -catenin gene has contributed to a better understanding of pathogenesis (14, 15). However, additional studies estimate that 46% of hepatic adenomas and between 35 to 80% of HCC have aberrant β -catenin cellular accumulation, not associated with mutations affecting the β -catenin gene. In addition, Axin1 and APC gene mutations are rare in HCC and thus, the mechanisms of wild-type β -catenin accumulation in the majority of HCC tumors have yet to be determined.^{16, 17, 18, 19} It is possible that other upstream components of this signaling pathway stabilize wild-type β -catenin in the cytoplasm to allow nuclear translocation and up-regulation of genes associated with the malignant phenotype.²¹

The Frizzled receptors of the Wnt/ β -catenin signal transduction cascade have been recently identified. They are composed of seven-transmembrane spanning domains and act as receptors for Wnt proteins.²² The canonical Wnt/Frizzled signaling network influences diverse biological processes ranging from cell fate determination to cell motility and proliferation.^{21, 23} The Wnt/Frizzled signal is also transduced by the non-canonical small G-protein RhoA/c-Jun NH2-terminal kinase (JNK), or the Ca²⁺-calmodulin-dependent protein kinase II (CamKII) and protein kinase C (PKC) (24).

Overexpression of Wnt ligands and/or Frizzled receptors have been found in tumors derived from esophagus, colon, and skin.^{25, 26, 27} The human Frizzled type 7 receptor (FZD7) has been cloned and identified.²⁵ Additional experiments revealed that FZD7 overexpression was able to stabilize wild-type β -catenin and induce its translocation into the nucleus; the functional consequence of this event was an increase in cell motility and migration. In contrast, down-regulation of the Wnt/FZD7 signal leads to inactivation of the β -catenin cascade and results in reduced cellular motility and invasiveness.^{21, 25} Recently, the *FZD7* gene was found to be overexpressed in most human HCC tumors related to chronic hepatitis B infection and in all human hepatoma cell lines tested. Indeed, enhanced expression of FZD7 was associated with downstream activation of the canonical Wnt/ β -catenin pathway in human HCC tumors and cell lines.²¹

In this context, transgenic mouse models provide unique opportunities to assess *in vivo* mechanisms involved in hepatocyte transformation.^{20, 28} In order to determine if activation of the Wnt/ β -catenin signal transduction cascade occurs at the Frizzled receptor level and is an early and common event during mammalian hepatocarcinogenesis, we established an experimental paradigm that employed a series of single, and double transgenic strains to explore expression of the Frizzled (*FZD*) gene family members in association with downstream activation of various components of this pathway. These transgenic lines overexpress either alone or in combination: 1) a transforming protein [SV40 large T-antigen (Tag)],²⁹ 2) an oncogene [(*c-myc*)],³⁰ 3) a viral transactivating protein [(HBx)],³¹ and 4) the insulin receptor substrate-1 (IRS-1) to provide a constitutive hepatocyte proliferative stimulus.³² All four transgenic lines developed HCC at different rates. We observed *FZD7* gene up-regulation in hepatic dysplasia during the evolution of HCC tumors in association with functional activation of the canonical Wnt/Frizzled/ β -catenin cascade. These observations suggest that early activation of this pathway is common during the process of mammalian hepatocyte transformation.

Transgenic Mice

Generation of F7 SV40-Tag single transgenic, and X/*c-myc* double transgenic mice with their corresponding non-transgenic littermates sharing the same genetic background – i.e., C57Bl/6 x DBA/2 for SV40-Tag and C57Bl/6 for X/*c-myc* – has

been previously described.^{29,31} The 93-7 WHV/*c-myc* and IRS-1 single transgenic mice^{30, 32} were mated to generate first generation (F1) IRS-1/*c-myc* double-transgenics, *c-myc* single-transgenics, and non-transgenic littermates, where all share the C57Bl/6 and FBV genetic backgrounds from WHV/*c-myc* (C57Bl/6) and IRS-1 (FBV) parental lines, respectively. The transgenes were identified by PCR analysis of DNA extracted from tail snipings using different sets of primers that cover a fragment of: 1) the human IRS-1 gene,³² 2) the woodchuck *c-myc* oncogene,³³ or 3) the hepatitis B virus X gene.³⁴ For SV40-Tag mice, the Tag transgene was carried on the Y chromosome allowing 100% penetrance in males. Animal housing and care were in accordance with NIH guidelines.

Histology

Hepatocellular carcinomas and the corresponding surrounding peritumorous liver parenchyma, as well as tumor-free livers, were obtained from adult females and males at different ages (1 to 9 months). Five μm -thick paraffin-embedded sections of liver were fixed in paraformaldehyde and stained with hematoxylin and eosin. Histopathological diagnosis was based upon criteria as previously described.³⁵

RT-PCR Assays

The amount of *FZD* mRNA was quantified in unknown samples by measuring the *Ct* value followed by normalization to *18S* ribosomal RNA (*18S rRNA*) after comparison to a standard curve for both *FZD* and *18S rRNA*. The ratio of *FZD/18S rRNA* was subsequently normalized to a calibrator (mean value obtained from normal liver derived from littermates of the same genetic background) and expressed as relative abundance of *FZD* mRNA. Standards were prepared with 10-fold dilutions of the corresponding PCR products cloned into the pCR[®]2.1 Vector (Invitrogen, Life Technology). The specificity of the *FZD* or *18S rRNA* inserts was provided by sequence analysis. Serial dilution of *FZD* and *18S rRNA* containing plasmids were aliquoted and stored at -20°C until use.

Primers were selected using the Primer3 website (www-genome.wi.mit.edu/cgi-bin/primer/primer3_www.cgi). Primers for *FZD* and *18S rRNA* respectively were as follows:*FZD1* (F: 5'-CAG AAC ACG TCC GAC AAA GG-3'

(SEQ ID NO:33), R: 5'-TCC TTC TCC CCC AGA AAGTG-3'(SEQ ID NO:34)), *FZD2* (F: 5'-GAG CAC CCT TTC CAC TGT CC-3'(SEQ ID NO:35), R: 5'-ACG GGC AAA ACG AGT CTC C-3'(SEQ ID NO:36)), *FZD3* (F: 5'-ATC CCC GAC TTG TGG ATT TG-3'(SEQ ID NO:37), R: 5'-ATG GTG GCG AAC AAT CTC G-3'(SEQ ID NO:38)), *FZD4* (F: 5'-GCA TGG AAG GAC CAG GTG AT-3'(SEQ ID NO:39), R: 5'-CTC CTT AGC TGA GCG GCT GT-3'(SEQ ID NO:40)), *FZD5* (F: 5'-GGA TTA TAA CCG AAG CGA AAC C-3'(SEQ ID NO:41), R: 5'-TGC GCA CCT TGT TGT AGA GTG-3'(SEQ ID NO:42)), *FZD6* (F: 5'-TTG GAT TTT GGT GTC CAA AGC-3'(SEQ ID NO:43), R: 5'-GGA GGG GCA CAC TGT TCA AT-3'(SEQ ID NO:44)), *FZD7* (F: 5'-TAC CTG CCA GAC CCA CCT TT-3'(SEQ ID NO:45), R: 5'-GCG AAC CGT CTC TCC TCT TC-3'(SEQ ID NO:46)), *FZD8* (F: 5'-GCT CTA CAA CCG CGT CAA GA-3'(SEQ ID NO:47), R: 5'-GCG CTC ATC CTG GCT AAA GA-3'(SEQ ID NO:48)), *FZD9* (F: 5'-GTA TGG AGG CAC CCG AGA AC-3'(SEQ ID NO:50), R: 5'-CAC GAG CGA CTC TTC TCC AC-3'(SEQ ID NO:51)), 18S rRNA (F: 5'-GGA CAC GGA CAG GAT TGA CA-3'(SEQ ID NO:52), R: 5'-ACC CAC GGA ATC GAG AAA GA-3'(SEQ ID NO:53)). BLASTN searches against dbEST and nr (the nonredundant set of GenBank database sequences) were conducted to confirm the gene specificity of the nucleotide sequences chosen for the primers as well as to establish the lack of DNA polymorphism. Primers were purchased from Invitrogen™ Life Technologies.

Total RNA was extracted from liver specimens by using TRIzol® Reagent (Invitrogen Life Technology). The quality of RNA samples was determined by electrophoresis through agarose gels and staining with ethidium bromide; the 18S and 28S ribosomal RNA bands were visualized under UV light. Total RNA was treated with DNase-I, RNase-free (Roche Diagnostics Corporation, Indianapolis, USA) to remove contaminating genomic DNA. Reverse transcription of 250 ng total RNA was performed in a final volume of 20 µl containing 1X RT-Buffer (50 mM Tris-HCl, 8 mM MgCl₂, 30 mM KCl, 1 mM dithiothreitol, pH 8.5), 250 µM each deoxynucleotide triphosphate, 40 units of RNase inhibitor, 3.2 µg random hexamers, 20 units of reverse transcriptase AMV all from Roche Diagnostics Corporation (Indianapolis, USA). The samples were incubated at 25°C for 10 minutes and 42°C for 1 hour. Reverse transcriptase was inactivated by heating at 99°C for 5 minutes, and cooling at 4°C for 5 minutes.

All PCR reactions were performed using an iCycler iQ™ Multi-Color Real Time PCR Detection System (Bio-Rad, Hercules, USA). For each run, a master mix was prepared on ice with 1X SYBR™ Green PCR Master Mix (Applied Biosystems, USA), 150 to 500 nM each primer, and cDNA from unknown samples (1 ng equivalent total RNA). The thermal cycling conditions comprised an initial step at 95°C for 10 minutes, followed by 40 cycles at 95°C for 15 seconds and 62°C for 1 minute. Experiments were performed in duplicate. Each PCR run included *FZD* and *18S* standard curves, a non-template control, and the unknown cDNAs analyzed for *FZD* and *18S* rRNA copy numbers.

Protein Extraction and Western Blot Analysis

Frozen mouse liver samples were homogenized and sonicated in lysis buffer [30 mM Tris (pH 7.5), 150 mM NaCl, 1% NP-40, 0.5% Na deoxycholate, 0.1% SDS, 10% glycerol, and 2 mM EDTA] containing the Complete Protease Inhibitor (Roche Molecular Biochemicals). After clarifying the extracts, protein concentrations were determined with the BCA Protein Assay Kit (Pierce) using BSA as standard. Cytosolic subcellular fractionations were performed as previously described.³⁶ Aliquots of 25 to 50 µg protein were resolved on SDS/PAGE and transferred onto PVDF membranes (NEN™ Life Science Products, Boston, MA) by electroblotting. The membranes were blocked with 5% nonfat dry milk in Tris-buffered saline containing 0.1% Tween 20 and then probed with a goat anti-mouse FZD7 polyclonal antibody diluted at 1:1,000 (RD Systems, Inc., Catalog number AF198), a mouse anti-β-catenin monoclonal antibody diluted at 1:500 (Transduction Laboratories), an anti-phospho Thr41, Ser45 β-catenin antibody diluted at 1:500 (Transduction Laboratories), or an anti-β-actin antibody (1:1,000), rabbit polyclonal antibodies for GSK3β, phospho-GSK3β (Ser9) (Cell Signaling Tec., Beverly, MA). The primary antibody was followed by incubation with a secondary antibody conjugated with horseradish peroxidase diluted 1:10,000 and then revealed with the chemiluminescence imaging Western Lightning (PerkinElmer™ Life Sciences, Boston, MA). The blots were standardized for equal protein binding by Ponceau S red staining or β-actin labeling. The immunoreactive bands were analyzed using NIH imaging software and all values were normalized to the loading controls.

A rabbit polyclonal antibody was prepared against a human derived FZD7 peptide

(QNTSDGSGGPGGGPTAYPTAPYLPD (SEQ ID NO:32), amino acids 163-187, NCBI Protein database accession no. BAA_34668) located in the extracellular domain of the receptor and sharing a high homology (identity = 92%, NCBI Pairwise BLAST) with the corresponding mouse peptide (QNTSDGSGGAGGSPTAYPTAPYLPD (SEQ ID NO:54), amino acids 163-187, NCBI Protein database accession no. NP_03203). This peptide did not share significant homology with other members of the Frizzled family or other known proteins (NCBI Nucleotide Blast). Specificity of the rabbit anti-FZD7 polyclonal antibody was determined by ELISA assay following absorption of preimmune and post-immune rabbit sera incubated with the specific peptide, or with another peptide serving as a negative control but also located in the extracellular domain of human FZD7 receptor (LGERDCGAPCEPGRANGLMYFKEEE (SEQ ID NO:55), amino acids 225-249, NCBI Protein database accession no. BAA_34668). Finally, the specificity of the antigen antibody interaction was further established by absorption of FZD7 immunoreactively as determined by Western blot analysis on tumor tissue with specific and not with non-relevant peptides as well as lack of FZD7 protein detection with addition of secondary antibody alone (data not shown).

Analysis of β -catenin gene

The PCR amplifications were performed on a PTC-100™ Programmable Thermal Controller (MJ Research, Inc.) using genomic DNA extracted and purified by standard techniques from frozen samples. Genomic DNA was amplified by a step-down PCR protocol using 100 ng of template DNA as described previously,³⁷ with a pair of primers, BCAT-EX1F, 5'-GCG TGG ACA ATG GCT ACT CAA G-3' (SEQ ID NO:56) (sense) and BCAT-EX3R, 5'-CTG GTC CTC ATC GTT TAG C-3' (SEQ ID NO:57) (antisense), which produced an amplicon encompassing the putative GSK3 β phosphorylation sites in β -catenin exon-2 (corresponding to human exon-3). PCR products were resolved in 1% agarose gel and visualized with ethidium bromide. No shorter PCR products corresponding to a deleted β -catenin gene were observed. Normal size PCR products were excised, and purified using the QIAEX II gel extraction kit (Qiagen, Inc.), and sequenced in both strands using the primers BCAT-EX2F, 5'-TGA TGG AGT TGG ACA TGG CCA TG-3' (SEQ ID NO:58) (sense) and

BCAT-EX2R, 5'-CCC ATT CAT AAA GGA CTT GGG AGG-3' (SEQ ID NO:59) (antisense).

Statistical Analysis

The *t*-Student test and the non-parametric Mann-Whitney test were used for data with StatView Software Version 5.0 (SAS Institute Inc.). Tests were considered significant when their *p* values were < 0.05.

Transgenic Models of HCC

Several transgenic murine models of hepatocarcinogenesis were employed since they develop preneoplastic hepatic lesions at different rates as well as by different molecular mechanisms during the evolution of tumors. A transforming protein (SV40 large T antigen) that abrogates p53 function^{29, 38} was used, as was an oncogene (*c-myc*) that provided both a proliferative and transforming stimulus,³⁰ a hepatitis B viral protein (HBx) with transcriptional transactivating properties that regulates cellular growth genes,³¹ and a constitutive hepatic proliferative stimulus provided by activation of the insulin/IGF-1 signal transduction pathway via IRS-1. In this model, hepatocyte proliferation is mediated by stimulation through the mitogen activated protein kinase (MAPK) cascade.³²

In preliminary studies, it was found that both single *c-myc* and double IRS-1/*c-myc* transgenics developed precancerous hepatocyte dysplasia at about 8 weeks of age and exhibit well differentiated HCC tumors of the trabecular histologic type at about 36 weeks (Figure 9D) as previously described.³⁰ As the HBx protein can accelerate *c-myc* induced tumors,³¹ it was found that the double X/*c-myc* transgenics developed HCC earlier than single *c-myc* or IRS-1/*c-myc* double transgenic animals (median, 29 weeks) (Figure 9G) as previously reported.³⁴ The most aggressive tumor model was the F7 strain of SV40-Tag single transgenic mice. These animals exhibited hepatocyte hyperplasia and dysplasia as early as 5 weeks followed by rapid onset of small cell type HCC at about 20 weeks (Fig. 9J).²⁹

Expression of Frizzled Receptors During Evolution

The murine *FZD* gene family is composed of 9 known homologues, *FZD1-9*.³⁹ Pilot experiments were performed on 10 animals with high degree dysplasia adjacent to

HCC. The mRNA levels of all Frizzled receptor genes were evaluated by RT-PCR. There was no expression of *FZD2*, *FZD3*, *FZD5*, and *FZD9* in normal liver, dysplasia or HCC (data not shown). The remaining *FZD1*, *FZD4*, *FZD6*, *FZD7*, and *FZD8* receptor genes displayed a significant and specific amplification signal as revealed by the melt curve, migration on agarose gels, and direct sequencing. Standard curves for *FZD* and *18S* genes showed a linear relationship between the *Ct* and the log of the copy number ($R^2 \geq 0.99$). The efficiency of the reactions was calculated as previously described⁴⁰ and ranged from 90 to 100% (data not shown). In order to compare different *FZD* mRNA levels, each value measured for *FZD* (recorded as *FZD* copy number per 109 *18S* rRNA copies) expression was normalized to the mean value obtained from the corresponding non-transgenic liver control group sharing the same genetic background.

FZD-1, -4, -6, -7, and -8 mRNA steady state levels were measured in HCC tumors and comparisons were made to: 1) precancerous regions characterized by widespread dysplastic hepatocytes and 2) non-transgenic normal liver. Precancerous liver was derived from the peritumorous region or from age-matched transgenic animals that had not yet developed HCC but contained multiple foci of dysplasia by histologic examination. It was observed that the *FZD7* gene was the only member of the *FZD* family to be up-regulated at the mRNA level in both precancerous liver ($n = 36$, $P < 0.001$) and HCC ($n = 20$, $P < 0.0001$) as compared to nontransgenic liver control ($n = 19$). *FZD7* mRNA levels were overexpressed in 19/36 (53%) of precancerous liver and 14/20 (70%) of HCC as determined by the cut off value equal to the mean value of non-transgenic livers $\pm 3SD$ ($P = 0.01$). In contrast, *FZD8* was substantially down regulated when comparing non-transgenic liver controls ($n = 15$) to dysplastic liver ($n = 22$, $P < 0.001$) (23%, 5/22 precancerous livers) and subsequently to HCCs ($n = 17$, $P < 0.0001$) (60%, 10/17 HCCs). To specifically address the question that *FZD* gene expression pattern may be restricted to unique HCC models, we compared findings among the four different transgenic models (*c-myc*, SV40, IRS-1/*c-myc*, and X/*c-myc*). As shown in Figs. 10A-10D, up-regulation of *FZD7* in dysplasia and HCC and down-regulation of *FZD8* gene expression principally in HCC were events common to all the animal models even when the tumors were presumably generated by different molecular mechanisms.

Relationship between FZD7 Expression and Evolution of HCC

To clarify the role of *FZD7* gene during the natural course of tumor development, expression levels in IRS-1/*c-myc*, X/*c-myc*, and SV40-Tag models were compared in the context of dysplasia advancing to HCC. As shown in Figure 11, SV40-Tag single transgenic mice develop dysplasia at 5 weeks and HCC at about 20 weeks in the setting of increasing *FZD7* levels. In contrast, IRS-1/*c-myc* double and *c-myc* single transgenics develop well-differentiated trabecular HCC at about 36 weeks of age in association with hepatic dysplasia; *FZD7* mRNA levels were also found to be up-regulated in 36 week-old dysplastic and tumorous liver areas. Finally, an intermediate model of dysplasia and HCC, as exemplified by the X/*c-myc* double transgenic model that develops well-differentiated trabecular HCC at 29 weeks was studied. Elevated *FZD7* gene expression was observed both in 12-week-old dysplastic liver and HCC.

Expression of FZD7 Protein

Correlations were made between *FZD7* mRNA and protein levels in dysplastic liver as well as HCC. Western blot analysis was performed with goat anti-mouse polyclonal antibody specific to FZD7 as shown in Fig. 12A. Representative results revealed up-regulation of the protein in early dysplasia and HCC similar to the *FZD7* mRNA results by RT-PCR. To further clarify the specificity of the protein band corresponding to FZD7 receptor observed on Western blot analysis with the goat polyclonal antibody (Fig. 12A), another rabbit polyclonal anti-peptide antibody was generated that reacts with both human and mouse FZD7 receptors. Specificity of the rabbit polyclonal antibody for FZD7 was confirmed by ELISA assay as described above. Furthermore, Western blot analysis using pre-immune and post-immune rabbit sera pre-incubated in the presence or absence of specific or non-relevant peptide confirmed the authenticity of the 75 KDa band found previously with both FZD7 polyclonal antibodies (data not shown). As shown in Fig. 12B, HCC cell lines Huh7 and HepG2 were used, expressing *FZD7* mRNA at high and low levels respectively by RT-PCR as positive controls.²¹ Finally, the FZD7 protein was clearly increased in HCC as generated by expression of the SV40-Tag transgene compared to tumor-free liver and correlated with the elevated *FZD7* mRNA levels (Fig. 11).

Relationship between Frizzled-7 Expression and β -Catenin in Tumors

The presence of β -catenin mutations during hepatocarcinogenesis in the mouse vary from 5 to 55% in HCC tumors and/or adenomas. β -catenin mutations have not yet been described in dysplastic liver,^{14, 15, 41} which implies that β -catenin mutations are a late genetic event. One aim of this study was to clarify the potential impact of FZD7 up-regulation on wild-type β -catenin accumulation in tumors, as well as the adjacent peritumorous dysplastic liver. The SV40-Tag transgenic model does not display β -catenin mutations but was found not suitable for this study since the peritumorous areas were often invaded by small microscopic HCC nodules.⁴² Therefore, FZD7 expression was compared to the β -catenin status in several tumors and dysplastic areas derived from the *X/c-myc* double transgenic strain. Histological examination had confirmed that the peritumorous regions were composed of dysplastic hepatocytes and were clearly separate from HCC tumors. The PCR analysis of genomic DNA and sequencing 4 of such tumors revealed no deletions or point mutations in the β -catenin exon 2 gene which includes the consensus motif for GSK3 β phosphorylation. Western blot analysis of protein extract derived from each tumor and corresponding peritumorous region revealed that FZD7 was overexpressed in both dysplastic and HCC areas in association with wild-type β -catenin cellular accumulation (Fig. 13). These findings suggest that the canonical Wnt/ β -catenin pathway may be activated by overexpression of FZD7 receptors similar to observations made with human HCC tumors and cell lines.²¹

Relationship of phospho-GSK3 β to β -catenin accumulation in dysplasia and HCC

Stabilization and accumulation of β -catenin in the cytosol is regulated by GSK3 β activity. In addition, elevated phospho-GSK3 β and β -catenin levels have been observed in HCC tissues.⁴³ To evaluate the potential effect of GSK3 β on the cellular accumulation of β -catenin, we measured GSK3 β and phospho- GSK3 β by Western blot analysis. As shown in Figs. 14A-14B, GSK3 β and phospho- GSK3 β levels were increased in late dysplasia (24 weeks) and HCC tumor (36 weeks) of *IRS-1/c-myc* as well as in *X/c-myc* mice (30 weeks) and SV40-Tag mice (20 weeks). Enhanced phosphorylation of GSK3 β has been associated with an increase in the ratio of total β -catenin/phospho- β -catenin and allows for stabilization and accumulation of β -catenin in the cytosol.⁴³ Therefore, such measurements were performed in cytosolic extracts

derived from *X/c-myc* double transgenic and SV40-Tag single transgenic animals; the level of total and Phospho- β -catenin was measured by Western blot analysis. As shown in Fig. 15, the phospho- β -catenin level was decreased in tumors (*X/c-myc*, SV40-Tag) and dysplasia (SV40-Tag) as expected. If the canonical pathway was activated, then the ratio of total β -catenin to phospho β -catenin (Thr41/Ser45) should be much higher in tumor compared to non-Tg liver which was indeed the case. This observation is consistent with the hypothesis that activation of the canonical Wnt/ β -catenin cascade occurs via overexpression of the FZD7 receptor murine models of in HCC.

Discussion

The expression patterns of the *FZD* gene family members have not been determined in HCC tumors derived from human, rat, or mouse liver tissues particularly in the context of functional activation of downstream components of Wnt/ β -catenin signal transduction cascade. In this study, quantitative RT-PCR assays were developed and employed to investigate hepatic expression of all nine *FZD* genes identified thus far during the multistep process of murine hepatocarcinogenesis. The data provided herein describe a specific up-regulation of a frizzled receptor gene in precancerous tissue and HCC tumors in four different animal models. Furthermore, there is an apparent association with cellular accumulation of wild-type β -catenin in tumors overexpressing FZD7 in the absence of β -catenin exon-2 mutations. There is enhanced serine 9 phosphorylation of GSK3 β and reduced Thr41/Ser56 phosphorylation of β -catenin leading or contributing to cellular accumulation of the protein.

These findings with four different transgenic models of HCC are similar to observations made with human HCC related to chronic hepatitis B infection.²¹ In that study, β -catenin accumulation was observed in over 90% of HCC tumors containing the wild type β -catenin gene in the context of high-level FZD7 expression. The FZD7 receptor was also highly overexpressed in six HCC cell lines and functional analysis revealed that *FZD7* mRNA levels correlated with robust Tcf/LEF transcriptional activity, and enhanced tumor cell motility and invasive properties. This biologic activity was blocked by a dominant negative mutant construct of FZD7 that decreased wild-type β -catenin accumulation in tumor cells. Taken together, the data suggest the canonical FZD7/ β -catenin pathway is more commonly involved in the molecular

pathogenesis of mammalian hepatocarcinogenesis than previously recognized since *FZD7* overexpression occurs early in the dysplastic liver and stabilizes wild type β -catenin levels within hepatocytes.

Previous studies have emphasized that at least two major genetic pathways may be involved during the development of HCC in rodent models as well as in human disease. One pathway is characterized by an intact Wnt signaling cascade in the setting of a mutator phenotype and chromosomal instability. The second is characterized by disruption of the Wnt signaling cascade, but the process is not limited to activating β -catenin mutations since there is nuclear accumulation of the protein in the setting of a wild-type gene; this pathway is associated with a low rate of loss of heterozygosity (LOH).^{13, 15, 20, 44, 45} Thus, β -catenin activation may be a very important event in both human and rodent hepatocarcinogenesis.^{14, 15, 20, 21, 41} However, the canonical Wnt/ β -catenin pathway has been found activated by β -catenin gene mutations in only 15-36% of human and murine HCC respectively; even more rare are Axin and APC mutations.^{45, 46, 47} Therefore, it is possible that upstream FZD receptors and their respective but yet unknown Wnt ligands are potential candidates for activation of this cascade in HCC. Indeed, several FZD receptor genes have been found overexpressed in human tumors of different origin such as the esophagus (*FZD7*), stomach (*FZD7*), and colon (*FZD1* and *FZD2*).^{25, 26, 48}

The human *FZD7* gene has been cloned and overexpression may lead to stabilization and nuclear translocation of wild-type β -catenin.^{21, 25} In the present study, four different murine transgenic models of hepatocarcinogenesis were used (*c-myc*, *IRS-1/c-myc*, *X/c-myc*, and *SV40-Tag*) and it was found that *FZD7* mRNA steady state levels are commonly up-regulated in approximately 70% of these tumors irrespective of the expressed transgene and in the context of a wild-type β -catenin gene. These findings are in general agreement with a 84% and 34% frequency of aberrant accumulation of wild type β -catenin protein in tumors derived from *c-myc*/E2F-1 and *c-myc* transgenic mice, respectively.²⁰ Finally, none of the age matched single transgenic *IRS-1* or *HBx* mice developed liver lesions or have increased *FZD7* expression (data not shown). The molecular mechanisms that promote upregulation of the *FZD7* gene are unknown. There are various possibilities that include: 1) paracrine or autocrine induction by Wnt ligands, 2) gene amplification, and 3) demethylation of the *FZD7* gene promotes sequences.

The stability of β -catenin in tumor cells is strongly enhanced by mutations or deletions affecting the GSK3 β phosphorylation site and the ubiquitination consensus sequences (49). Stabilized forms of β -catenin accumulate in the cytoplasm, translocate to the nucleus and bind LEF/Tcf factors, thereby stimulating transcription of a number of cellular targets genes.⁵⁰ In contrast to previous studies showing a significant correlation between the presence of stabilizing mutations of the gene and nuclear accumulation of the protein in human liver tumors,^{14, 37} several studies have failed to detect nuclear accumulation of mutated β -catenin protein in murine HCC.^{51, 52} Furthermore, recent findings have suggested that modest cytosolic accumulation of β -catenin can induce neoplastic transformation of normal epithelial cells,^{53, 54} and may transduce Wnt signals by exporting Tcf from the nucleus or by activating it in the cytoplasm.⁵⁵

β -catenin accumulation in tumor derived protein extracts was also investigated, and both cytoplasmic and nuclear accumulation in murine as well as in human tumors²¹ that contain the wild type β -catenin gene was found. Of interest here is the finding *in vivo* that FZD7 gene up-regulation is associated enhanced accumulation of wild-type β -catenin protein in dysplastic hepatic foci prior to the development of HCC. In this context, there is also enhanced expression and phosphorylation of GSK3 β and reduced Ser/Thr phosphorylation of β -catenin which presumably leads to cellular accumulation. These observations support previous findings in human tumors that demonstrates overexpression of FZD7 stabilizes the APC/ β -catenin complex and promote wild-type β -catenin translocation into the nucleus.²⁵

In view of a general consensus that tumor development proceeds through a succession of genetic changes that confers growth advantage,⁵⁶ it seems likely that activation of the Wnt/FZD7/ β -catenin cascade is directly involved in the progression from dysplasia to frank tumor formation and thus represents an early event in the generation of a malignant phenotype by promoting the biologic activity of cell migration and invasion.²¹ There was a striking down-regulation of FZD8 in 23% of precancerous liver with dysplasia and 60% of HCC tumors. Indeed, FZD8 down-regulation is a frequent phenomenon in HCC compared to the corresponding precancerous liver (6-fold mean decrease). Little is known about FZD8 function during hepatic oncogenesis. However, it is of interest that FZD8 can activate c-Jun N-terminal

kinases (JNK) and trigger apoptotic cell death in a β -catenin independent manner during gastrulation of *Xenopus* embryos.⁵⁷

Approximately 25% of murine tumors with a wild-type gene have little if any abhorrent accumulation of β -catenin. This finding raises the possibility there may be involvement of Wnt/Frizzled/ β -catenin independent pathways as recently suggested by human studies.⁴⁵ In conclusion, this study suggests that the FZD7/ β -catenin signaling pathway plays a key role in the multistep process of murine hepatocarcinogenesis. FZD7 up-regulation is associated with increased levels and phosphorylation GSK3 β and promotes β -catenin stability and subsequent accumulation in the cytosol in both tumors and adjacent dysplastic tissues from four different HCC transgenic models. Because of similar findings in human tumors,²¹ these transgenic mice are realistic animal models and provide novel molecular targets to access various therapeutic approaches in this devastating disease.

References

1. Murray, C.J.L., and Lopez, A.D. 1997. Mortality by cause for eight regions of the world: global burden of disease study. *Lancet* **349**:1269-1276.
2. Caselmann, W.H. and Alt, M. 1996. Hepatitis C virus infection as a major risk factor for hepatocellular carcinoma. *J. Hepatol.* **24**:61-66.
3. Anthony, P.P. 2001. Hepatocellular carcinoma: an overview. *Histopathology* **39**: 109-118.
4. El-Serag, H.B., Mason, A.C. 1999. Rising incidence of hepatocellular carcinoma in the United States. *N. Engl. J. Med.* **340**(10):745-50.
5. Nagai, H., Pineau, P., Tiollais, P., Buendia, M.A., and Dejean, A. 1997. A comprehensive allelotyping of human hepatocellular carcinoma. *Oncogene* **14**:2927-2933.
6. Idilman, R., De Maria, N., Colantoni, A., and Van Thiel, D. 1998. Pathogenesis of hepatitis B and C-induced hepatocellular carcinoma. *J. Viral. Hepat.* **5**: 285-299.
7. Zhang, X.K., Huang, D.P., Qiu, D.K., and Chiu, J.F. 1990. The expression of c-myc and c-N-ras in human cirrhotic livers, hepatocellular carcinomas and liver tissue surrounding the tumors. *Oncogene* **5**:909-914.
8. de Souza, A.T., Hankins, G.R., Washington, M.K., Orton, T.C., and Jirtle, R.L. 1995. M6P/IGF2R gene is mutated in human hepatocellular carcinomas with loss of heterozygosity. *Nat. Genet.* **11**: 447-449.
9. Cariani, E., Lasserre, C., Seurin, D., Hamelin, B., Kemeny, F., Franco, D., Czech, M.P., Ullrich, A., and Brechot, C. 1988. Differential expression of insulin-like growth factor II mRNA in human primary liver cancers, benign liver tumors, and liver cirrhosis. *Cancer Res.* **48**: 6844-6849.

10. Yeh, Y.C., Tsai, J.F., Chuang, L.Y., Yeh, H.W., Tsai, J.H., Florine, D.L., and Tam, J.P. 1987. Elevation of transforming growth factor alpha and its relationship to the epidermal growth factor and alpha-fetoprotein levels in patients with hepatocellular carcinoma. *Cancer Res.* 47: 896-901.
11. Hsu, I.C., Metcalf, R.A., Sun, T., Welsh, J.A., Wang, N.J., and Harris, C.C. 1991. Mutational hotspot in the p53 gene in human hepatocellular carcinomas. *Nature* 350:427-428.
12. Zhang, X., Xu, H.J., Murakami, Y., Sachse, R., Yashima, K., Hirohashi, S., Hu, S.X., Benedict, W.F., and Sekiya, T. 1994. Deletions of chromosome 13q, mutations in Retinoblastoma 1, and retinoblastoma protein state in human hepatocellular carcinoma. *Cancer Res.* 54: 4177-4182.
13. Zimonjic, D.B., Keck, C.L., Thorgeirsson, S.S., and Popescu, N.C. 1999. Novel recurrent genetic imbalances in human hepatocellular carcinoma cell lines identified by comparative genomic hybridization. *Hepatology* 29: 1208-1214.
14. de la Coste, A., Romagnolo, B., Billuart, P., Renard, C.A., Buendia, M.A., Soubrane, O., Fabre, M., Chelly, J., Beldjord C., Kahn, A., and Perret, C. 1998. Somatic mutations of the β -catenin gene are frequent in mouse and human hepatocellular carcinoma. *Proc. Natl. Acad. Sci. USA* 95: 8847-8851.
15. Calvisi, D.F., Factor, V.M., Loi, R., and Thorgeirsson, S.S. 2001. Activation of β -catenin during hepatocarcinogenesis in transgenic mouse models. *Cancer Res.* 61: 2085-2091.
16. Torbenson, M., Lee, J.H., Chofi, M., Gag, W., Abraham, S.C., Montgomery, E., Boitnott, J., Wu, T.T. 2002. Hepatic adenomas: analysis of sex steroid receptor status and the Wnt signaling pathway. *Mod. Pathol.* 15(3):189-96.

17. Hsu, H.C., Jeng, Y.M., Mao, T.L., Chu, J.S., Lai, P.L., and Peng, S.Y. 2000. β -catenin mutations are associated with a subset of low-stage hepatocellular carcinoma negative for hepatitis B virus and with favorable prognosis. *Am. J. Pathol.* **157**:763-770.
18. Devereux, T.R., Stern, M.C., Flake, G.P., Yu, M.C., Zhang, Z.Q., London, S.J., and Taylor, J.A. 2001. CTNNB1 mutations and beta-catenin protein accumulation in human hepatocellular carcinomas associated with high exposure to aflatoxin B1. *Mol. Carcinog.* **31**:68-73.
19. Wong, C.M., Fan, S.T., and Ng, I.O. 2001. β -catenin mutation and over-expression in hepatocellular carcinoma: clinicopathologic and prognostic significance. *Cancer* **92**:136-145.
20. Calvisi, D.F., Factor, V.M., Ladu, S., Conner, E.A., Thorgeirsson, S.S. 2004. Disruption of β -catenin pathway or genomic instability define two distinct categories of liver cancer in transgenic mice. *Gastroenterology* **126**:1374-1386.
21. Merle, P., de la Monte, S.M., Kim, M., Herrmann, M., Tanaka, S., von dem Bussche, A., Kew, M., Trepo, C., Wands, J.R. 2004. Functional consequences of frizzled-7 receptor overexpression in human hepatocellular carcinoma. *Gastroenterology* In press.
22. Bhanot, P., Brink, M., Samos, C.H., Hsieh, J.C., Wang, Y., Macke, J.P., Andrew, D., Nathans, J., and Nusse, R. 1996. A new member of the Frizzled family from *Drosophila* functions as a Wingless receptor. *Nature* **38**:225-230.
23. Jones, S.E., and Jomary, C. 2002. Secreted Frizzled-related proteins: searching for relationships and patterns. *BioEssays* **24**:811-820.

24. Kuhl, M., Sheldahl, L.C., Park, M., Miller, J.R., and Moon, R.T. 2000. The Wnt/Ca²⁺ pathway. A new vertebrate Wnt signaling pathway takes shape. *Trends Genet.* **16**:279-283.
25. Tanaka, S., Akiyoshi, T., Mori, M., Wands, J.R., and Sugimachi, K. 1998. A novel frizzled gene identified in human esophageal carcinoma mediates APC/ β -catenin signals. *Proc. Natl. Acad. Sci. USA* **95**:10164-10169.
26. Holcombe, R.F., Marsh, J.L., Waterman, M.L., Lin, F., Milovanovic, T., and Truong, T. 2002. Expression of Wnt ligands and Frizzled receptors in colonic mucosa and in colon carcinoma. *Mol. Pathol.* **55**:220-226.
27. Weeraratna, A.T., Jiang, Y., Hostetter, G., Rosenblatt, K., Duray, P., Bittner, M., and Trent, J.M. 2002. Wnt5a signaling directly affects cell motility and invasion of metastatic melanoma. *Cancer Cell* **3**: 279-288.
28. Fausto, N. 1999. Mouse liver tumorigenesis: models, mechanisms, and relevance to human disease. *Seminars in Liver Disease* **19**: 243-252.
29. Dubois, N., Bennoun, M., Allemand, I., Molina, T., Grimmer, G., Daudet-Monsac, M., Abelanet, R., and Briand, P. 1991. Time-course development of differentiated hepatocarcinoma and lung metastasis in transgenic mice. *J. Hepatol.* **13**: 227-239.
30. Etienneble, J., Degott, C., Renard, C.A., Fourel, G., Shamoon, B., Vitvitski-Trepo, L., Hsu, T.Y., Tiollais, P., Babinet, C., and Buendia, M.A. 1994. Liver-specific expression and high oncogenic efficiency of a c-myc transgene activated by woodchuck hepatitis virus insertion. *Oncogene* **9**:727-737.
31. Terradillos, O., Billet, O., Renard, C.A., Levy, R., Molina, T., Briand, P., and Buendia, M.A. 1997. The hepatitis B virus X gene potentiates c-myc-induced liver oncogenesis in transgenic mice. *Oncogene* **14**:395-404.

32. Mohr, L., Tanaka, S., and Wands, J.R. 1998. Ethanol inhibits hepatocyte proliferation in insulin receptor substrate-1 transgenic mice. *Gastroenterology* 115:1558-1565.
33. Merle, P., Chevallier, M., Levy, R., Maisonnas, M., Terradillos, O., Si Ahmed, S.N., Trepo, C., Buendia, M.A., and Vitvitski, L. 2001. Preliminary results of interferon-alpha therapy on woodchuck hepatitis virus-induced hepatocarcinogenesis : possible benefit in female transgenic mice. *J. Hepatol.* 34:562-569.
34. Merle, P., Barraud, L., Lefrançois, L., Chevallier, M., Maisonnas, M., Bordes, I., Savre-Train, I., Trepo, C., and Vitvitski, L. 2003. Interferon-alpha therapy dose- and time-dependently delays *Hepadnavirus*-related hepatocarcinogenesis in *X/myc* transgenic mice. *Oncogene* 22:2762-2771.
35. Frith, C.H., Ward, J.M., and Turusov, V.S. 1994. Tumors of the liver. In *Pathology of Tumors in Laboratory Animals*. V. Turusov and U. Mohr, editors. IARC. Lyon, France. Vol. 2:223-270.
36. Maloney, J.A., Tsygankova, O., Szot, A., Yang, L., Li, Q., Williamson, J.R. 1998. Differential translocation of protein kinase C isozymes by phorbol esters, EGF, and ANG II in rat liver WB cells. *Am. J. Physiol.* 274:C974-982.
37. Tran Van Nhieu, J., Renard, C.A., Wei, Y., Cherqui, D., Zafrani, E.S., and Buendia, M.A. 1999. Nuclear accumulation of mutated β -catenin in hepatocellular carcinoma is associated with increased cell proliferation. *Am. J. Pathol.* 155:703-710.
38. Moore, M., Teresky, A.K., Levine, A.J., and Seiberg, M. 1992. p53 mutations are not selected for in simian virus 40 T-antigen-induced tumors from transgenic mice. *J. Virol.* 66:641-649.
39. Giles, R.H., van Es, J.H., and Clever, H. 2003. Caught up in a Wnt storm: Wnt signaling in cancer. *Biochim. Biophys. Acta* 1653:1-24.

40. Bieche, I., Laurendeau, I., Tozlu, S., Olivi, M., Vidaud, D., Lidereau, R., and Vidaud, M. 1999. Quantitation of *MYC* gene expression in sporadic breast tumors with a real-time reverse transcription-PCR assay. *Cancer Res.* **59**:2759-2765.
41. Anna, C.H., Iida, M., Sills, R.C., and Devereux, T.R. 2003. Expression of potential beta-catenin targets, cyclin D1, c-Jun, c-Myc, E-cadherin, and EGFR in chemically induced hepatocellular neoplasms from B6C3F1 mice. *Toxicol. Appl. Pharmacol.* **190**:135-145.
42. Umeda, T., Yamamoto, T., Kajino, K., and Hino, O. 2000. β -catenin mutations are absent in hepatocellular carcinomas of SV40 T-antigen transgenic mice. *Int. J. Oncol.* **16**:1133-1136.
43. Ban, K.C., Singh, H., Krishnan, R., Seow, H.F. 2003. GSK-3 β phosphorylation and alteration of β -catenin in hepatocellular carcinoma. *Cancer letters* **199**:201-208.
44. Legoix, P., Bluteau, O., Bayer, J., Perret, C., Balabaud, C., Belghiti, J., Franco, D., Thomas, G., Laurent-Puig, P., and Zucman-Rossi, J. 1999. Beta-catenin mutations in hepatocellular carcinoma correlate with a low rate of loss of heterozygosity. *Oncogene* **18**:4044-4046.
45. Laurent-Puig, P., Legoix P, Bluteau O, Belghiti J, Franco D, Binot F, Mones G, Thomas G, Bioulac-Sage P, and Zucman-Rossi J. 2001. Genetic alterations associated with hepatocellular carcinomas define distinct pathways of hepatocarcinogenesis. *Gastroenterology* **120**:1763-1773.
46. Huang, H., Fuji, H., Sankila, A., Mahler-Araujo, B.M., Matsuda, M., Cathomas, G., and Ohgaki, H. 1999. Beta-catenin mutations are frequent in human hepatocellular carcinomas associated with hepatitis C virus infection. *Am. J. Pathol.* **155**:1795-1801.

47. Satoh, S., Daigo, Y., Furukawa, Y., Kato, T., Miwa, N., Nishiwaki, T., Kawasoe, T., Ishiguro, H., Fujita, M., Tokino, T., et al. 2000. AXIN1 mutations in hepatocellular carcinomas, and growth suppression in cancer cells by virus-mediated transfer of AXIN1. *Nat. Genet.* 24:245-250.
48. Kirikoshi, H., Sekihara, H., and Katoh, M. 2001. Up-regulation of Frizzled-7 (FZD7) in human gastric cancer. *Int. J. Oncol.* 19:111-115.
49. Morin, P.J., Sparks, A.B., Korinek, V., Barker, N., Clevers, H., Vogelstein, B., and Kinzler, K.W. 1997. Activation of beta-catenin-Tcf signaling in colon cancer by mutations in beta-catenin or APC. *Science* 275:1787-1790.
50. Morin, P.J. Beta-catenin signaling and cancer. 1999. *Bioessays* 21:1021-1030.
51. Devereux, T.R., Anna, C.H., Foley, J.F., White, C.M., Sills, R.C., and Barrett, J.C. 1999. Mutation of beta-catenin is an early event in chemically induced mouse hepatocellular carcinogenesis. *Oncogene* 18:4726-4733.
52. Renard, C.A., Fourel, G., Bralet, M.P., Degott, C., de La Coste, A., Perret, C., Tiollais, P., and Buendia, M.A. 2000. Hepatocellular carcinoma in WHV/N-myc2 transgenic mice: oncogenic mutations of beta-catenin and synergistic effect of p53 null alleles. *Oncogene* 19:2678-2686.
53. Kolligs, F.T., Hu, G., Dang, C.V., and Fearon, E.R. 1999. Neoplastic transformation of RK3E by mutant beta-catenin requires deregulation of Tcf/Lef transcription but not activation of c-myc expression. *Mol. Cell. Biol.* 19:5696-5706.
54. Orford, K., Orford, C.C., and Byers, S.W. 1999. Exogenous expression of beta-catenin regulates contact inhibition, anchorage-independent growth, anoikis, and radiation-induced cell cycle arrest. *J. Cell Biol.* 146:855-868.

55. Chan, S.K., and Struhl, G. 2002. Evidence that Armadillo transduces wingless by mediating nuclear export or cytosolic activation of Pangolin. *Cell* 111:265-280.
56. Hanahan, D., and Weinberg, R.A. 2000. The hallmarks of cancer. *Cell* 100:57-70.
57. Lisovsky, M., Itoh, K., and Sokol, S.Y. 2002. Frizzled receptors activate a novel JNK-dependent pathway that may lead to apoptosis. *Curr. Biol.* 12:53-58.

A number of embodiments of the invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. Accordingly, other embodiments are within the scope of the following claims.

WHAT IS CLAIMED IS:

1. A method of determining whether a liver cell is, or is at risk for becoming, a cancer cell, the method comprising:
 - (a) providing a test liver cell;
 - (b) determining whether the cell's level of FZD7 expression is higher than that of a control cell; and
 - (c) classifying the test cell as a cancer cell or at risk for becoming a cancer cell, if the test cell's level of FZD7 expression is higher than that of a the control cell,
2. A method of determining whether a test tissue sample comes from a patient that is suffering from or at risk for liver cancer, the method comprising:
 - (a) providing a liver test tissue sample obtained from the patient; and
 - (b) determining whether the level of FZD7 expression in the test tissue sample
- 5 is higher than that in a comparable tissue sample obtained from a healthy individual, wherein a higher level of expression in the test tissue sample is an indication that the patient is suffering from or is at risk for cancer.
3. The method of claim 1 or 2, wherein determining the level of FZD7 expression includes determining the amount of FZD7 mRNA in the test cell or test tissue sample.
4. The method of claim 3, wherein the amount of FZD7 mRNA is determined using a Northern blot assay or an RT-PCR assay.
5. The method of claim 1 or 2, wherein determining the level of FZD7 expression includes determining the amount of FZD7 protein in the test cell or test tissue sample.
6. The method of claim 5, wherein the amount of FZD7 protein is determined using an antibody.
7. The method of claim 6, wherein the antibody binds to SEQ ID NOS:32 or 55.

8. The method of claim 1 or 2, further comprising determining whether the test cell's or test tissue's level of FZD8 expression is lower than that of a control cell or control tissue, wherein a lower level of expression of FZD8 indicates that (i) the test cell is, or is at risk for becoming, a cancer cell or (ii) the patient is suffering from or is at risk for cancer.
9. The method of claim 2, wherein the tissue sample provided in (a) is tumorous tissue or peritumorous tissue.
10. The method of claim 2, further comprising:
 - (c) determining whether the level of FZD8 expression in the test tissue sample is lower than that in a tissue sample obtained from a healthy individual, wherein a lower level of expression of FZD8 is an indication that the patient is suffering from or at risk for cancer.
11. Use of a compound that reduces Wnt/ FZD7 signaling in FZD7-expressing cells for the manufacture of a medicament for the treatment of cancer.
12. Use of a compound capable of reducing Wnt/ FZD7 signaling in FZD7-expressing cells for the manufacture of a medicament for reducing motility of a liver cancer cell.
13. The use of claim 11 or 12, wherein the medicament is non-lethal to FZD7-expressing cells.
14. The use of claim 11 or 12, wherein the medicament, when administered to a cancer patient, reduces FZD7 expression in the patient.
15. The use of claim 11 or 12, wherein the compound is
 - (i) an antisense oligonucleotide;
 - (ii) a double stranded RNA (dsRNA) comprising a nucleotide sequence that hybridizes under physiological conditions to a FZD7 nucleotide sequence;
 - (iii) an isolated FZD7 receptor or a Wnt binding fragment thereof; or
 - (iv) a genetic construct encoding a truncated form of FZD7.

16. The use of claim 15, wherein the compound is the genetic construct; and the medicament is suitable for administration to a liver.
17. The use of claim 15, wherein the compound is a genetic construct encoding a truncated form of FZD7 that lacks (a) FZD7's intracellular domain or (b) FZD7's intracellular and transmembrane domain.
18. A transgenic, non-human animal whose genome comprises a *c-myc* transgene and an IRS-1 transgene, wherein the animal exhibits increased susceptibility to hepatocellular carcinoma, as compared to a wild type counterpart.
19. The transgenic animal of claim 18, wherein the animal is a mammal.
20. The transgenic animal of claim 18, wherein the animal is a primate, pig, rodent, rabbit, cow, horse, cat, dog, sheep or goat.
21. The transgenic animal of claim 18, wherein the animal develops precancerous hepatocyte dysplasia in less than about 60 or in less than about 90 days from birth.
22. A method of identifying a compound for treating liver cancer, the method comprising:
 - (a) administering a test compound to the transgenic animal of claim 18; and
 - (b) determining whether the compound reduces the incidence or level of liver cancer in the transgenic animal.
23. A method of identifying an anticancer agent, the method comprising:
 - (a) administering a test compound to a cell that expresses FZD7; and
 - (b) determining whether the compound reduces Wnt/FZD7 signaling in the cell,wherein a compound that reduces Wnt/FZD7 signaling is a candidate anticancer agent.
24. The method of claim 23, wherein (b) is performed by
 - (i) determining whether the compound reduces expression of FZD7 in the cell;

- (ii) detecting the amount of FZD7 mRNA in the cell; or
- (iii) detecting the amount of FZD7 protein in the cell.

25. The method of claim 23, further comprising:

- (c) determining whether the candidate anti-cancer agent is capable of:
 - (i) reducing Wnt/FZD7 signaling in a cell;
 - (ii) reducing cancer cell motility;
 - (iii) reducing β -catenin accumulation in a cancer cell; or
 - (iv) treating cancer *in vitro* or *in vivo*;

wherein a candidate that is capable of at least one of (i) to (iv) is an anti-cancer agent.

26. The method of claim 23, further comprising:

- (c) determining whether the candidate compound inhibits cancer when administered to an animal, wherein a candidate compound that inhibits cancer is an anti-cancer agent.

27. A method for identifying an anti-cancer agent, the method comprising:

- (a) providing a polypeptide comprising the amino acid sequence of a FZD7 receptor protein or a fragment thereof;
- (b) contacting the polypeptide with a test compound;
- (c) detecting binding between the polypeptide and the test compound;
- (d) selecting the test compound if it binds to the polypeptide, wherein a selected test compound is a candidate anti-cancer agent; and
- (e) determining whether the candidate anti-cancer agent is capable of:
 - (i) reducing Wnt/FZD7 signaling in a cell;
 - (ii) reducing cancer cell motility;
 - (iii) reducing β -catenin accumulation in a cancer cell; or
 - (iv) treating cancer *in vitro* or *in vivo*;

wherein a candidate that is capable of at least one of (i) to (iv) is an anti-cancer agent.

28. The method of claim 27, wherein the polypeptide is

- (i) a naturally occurring polypeptide,

- (ii) a recombinant polypeptide;
- (iii) a polypeptide that comprises SEQ ID NO:2;
- (iv) a polypeptide that comprises SEQ ID NO:2 and at least one non-FZD7 sequence;
- (v) a polypeptide expressed on the surface of a cell; or
- (v) an isolated polypeptide.

29. A compound for treating liver cancer identified by the method of claim 22 or an anticancer agent identified by the method of any one of claims 23-28 for use in the treatment of liver cancer or cancer, respectively.

30. Use of a compound for treating liver cancer identified by the method of claim 22 or an anticancer agent identified by the method of any one of claims 23-28 for use in the preparation of a medicament for the treatment of liver cancer or cancer, respectively.

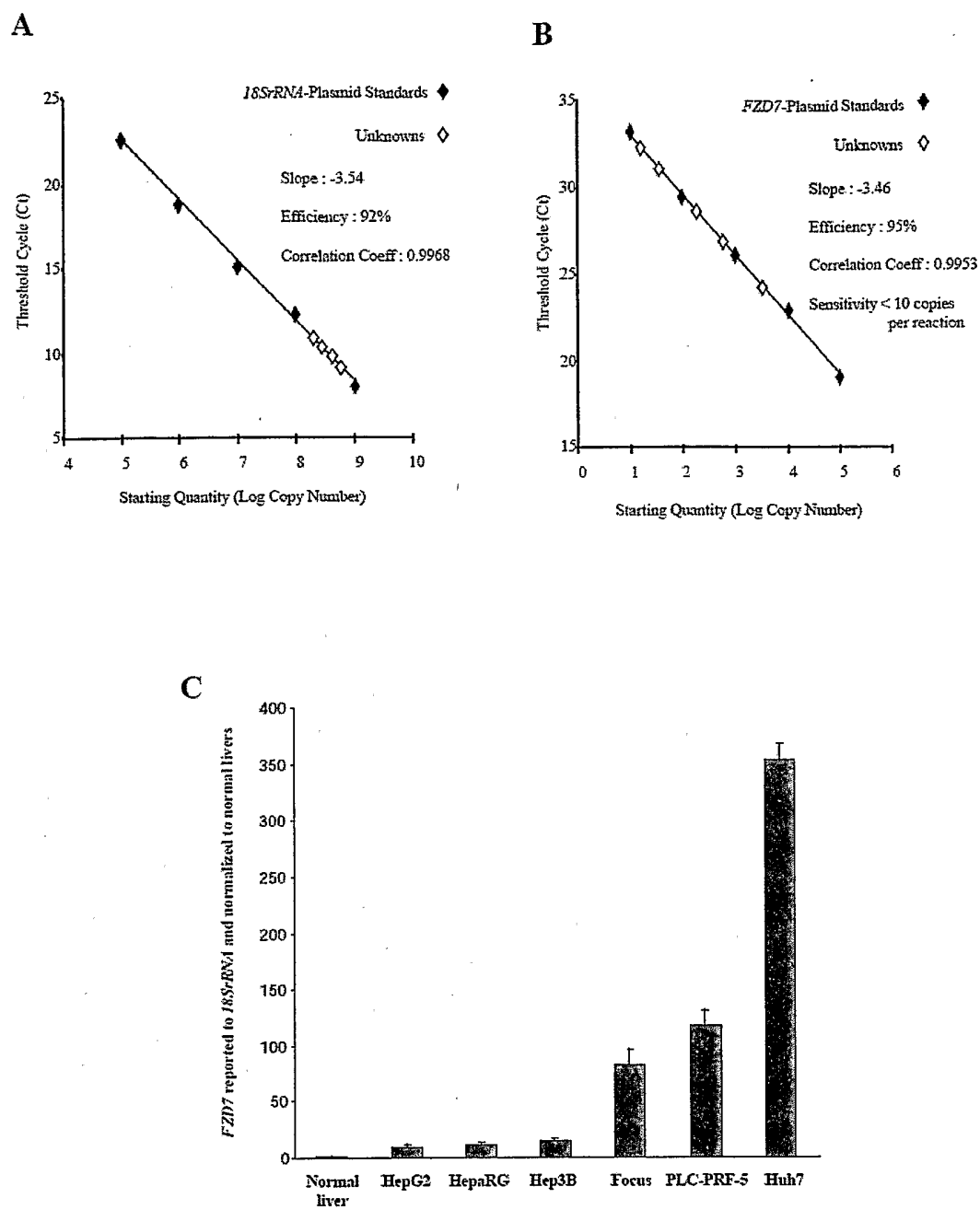
31. A method of making a non-human transgenic animal susceptible to hepatocellular carcinoma (HCC), the method comprising:

(a) crossing a first parental animal whose genome comprises a *c-myc* transgene that is expressed in hepatic cells with a second parental animal whose genome comprises a IRS-1 transgene that is expressed in hepatic cells; and

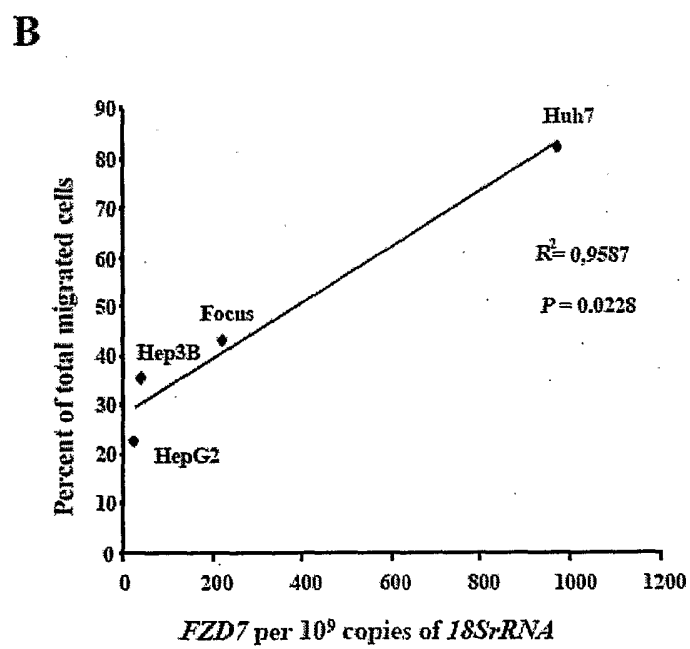
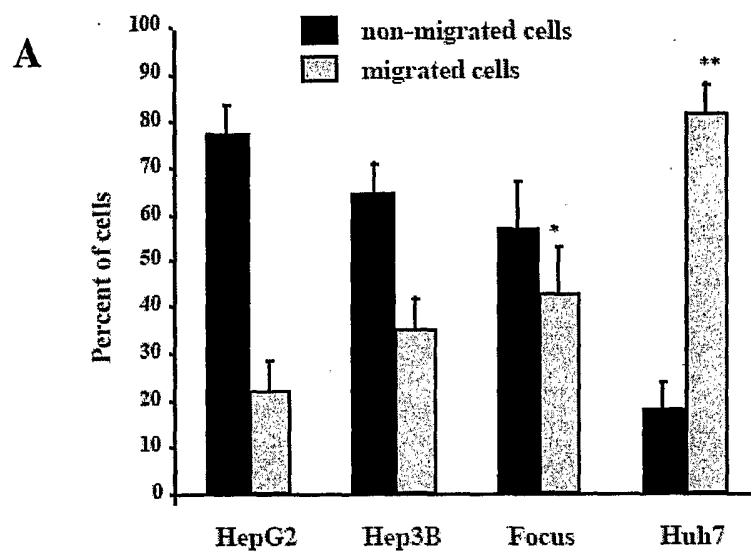
(b) isolating a progeny animal that expresses the transgenes of both parental animals and is a transgenic animal susceptible to hepatocellular carcinoma.

32. The method of claim 31, wherein the progeny animal is a mammal.

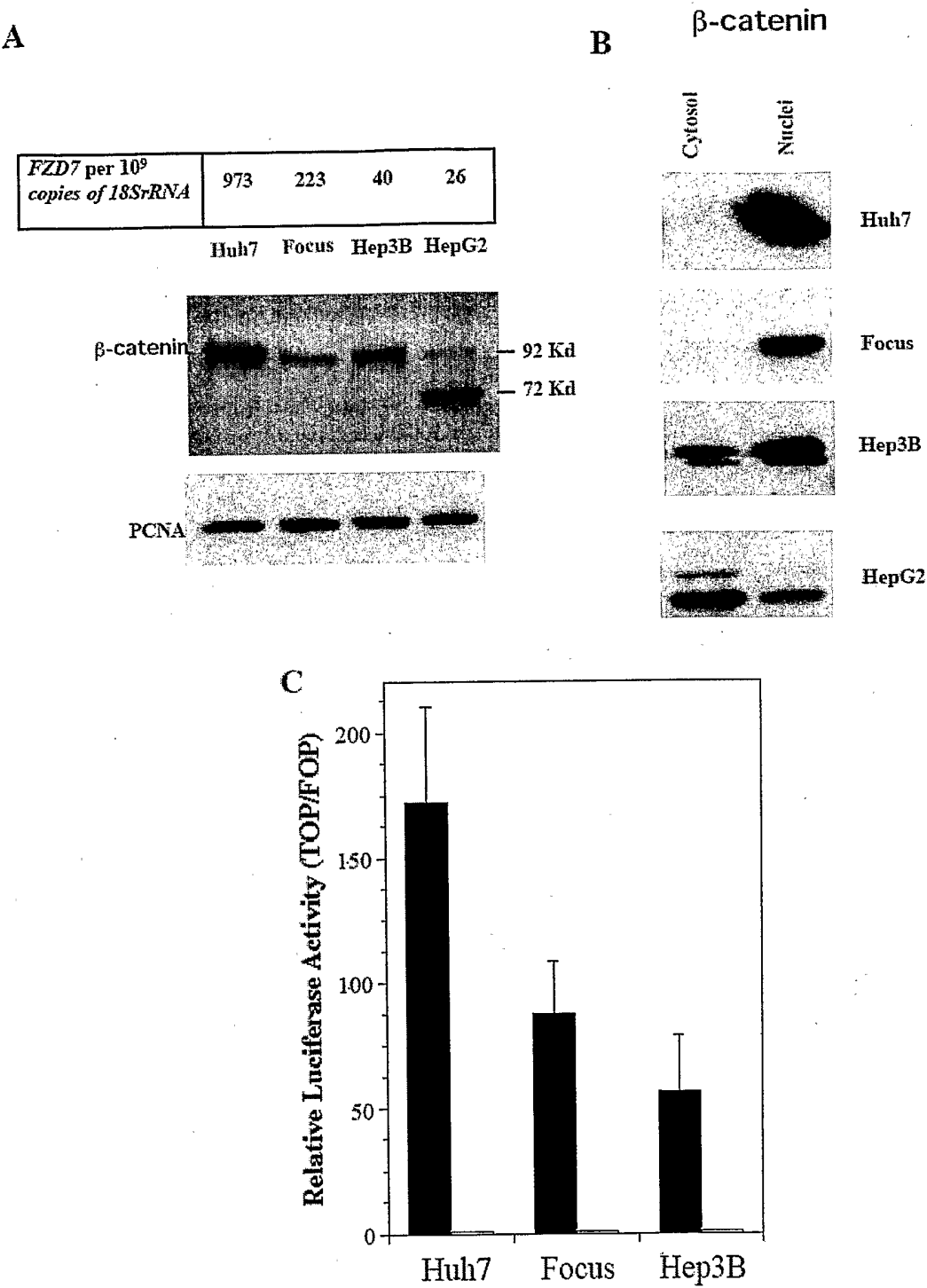
33. The method of claim 31, wherein the animal is a primate, pig, rodent, rabbit, guinea pig, hamster, cow, horse, cat, dog, sheep or goat.



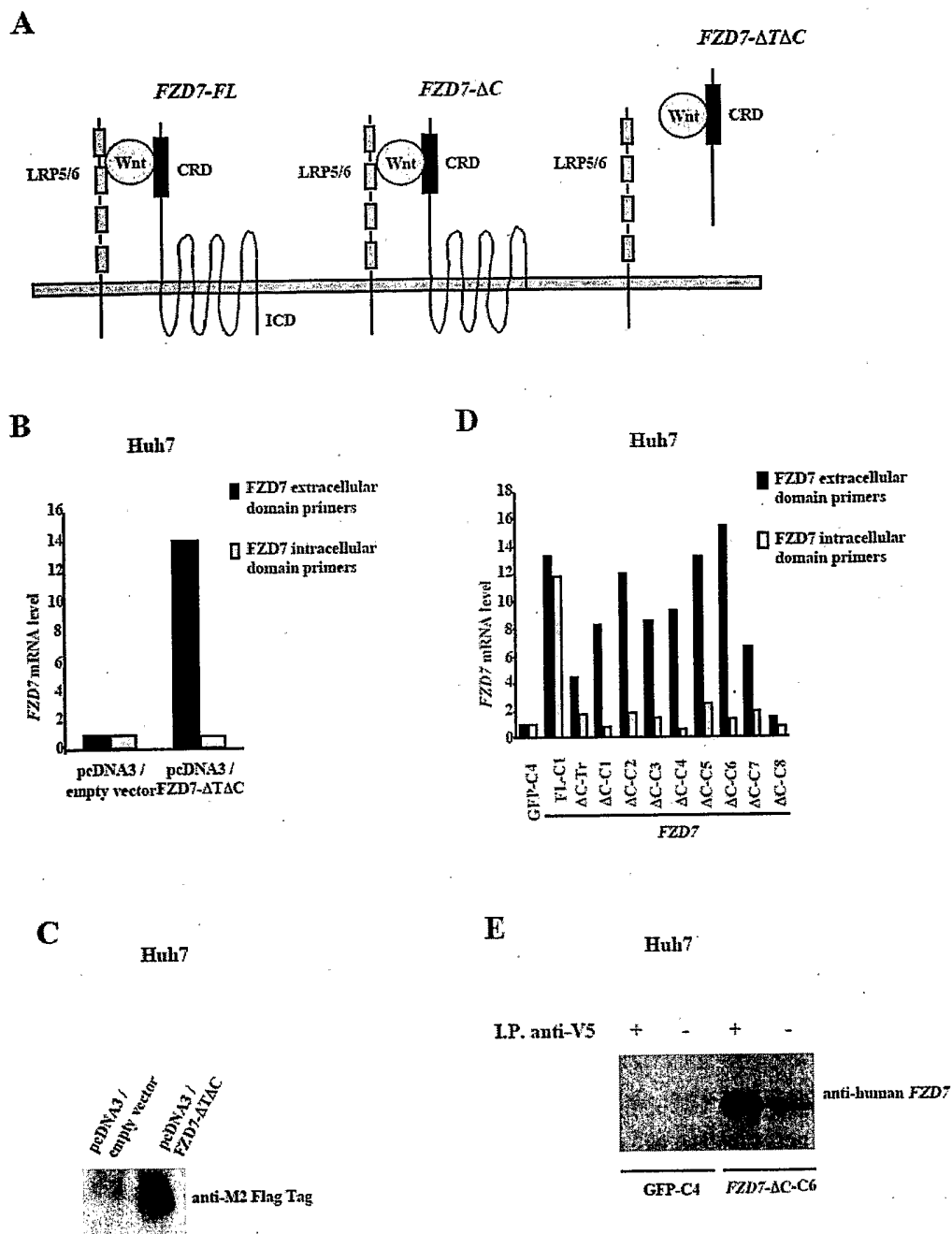
FIGS. 1A-1C



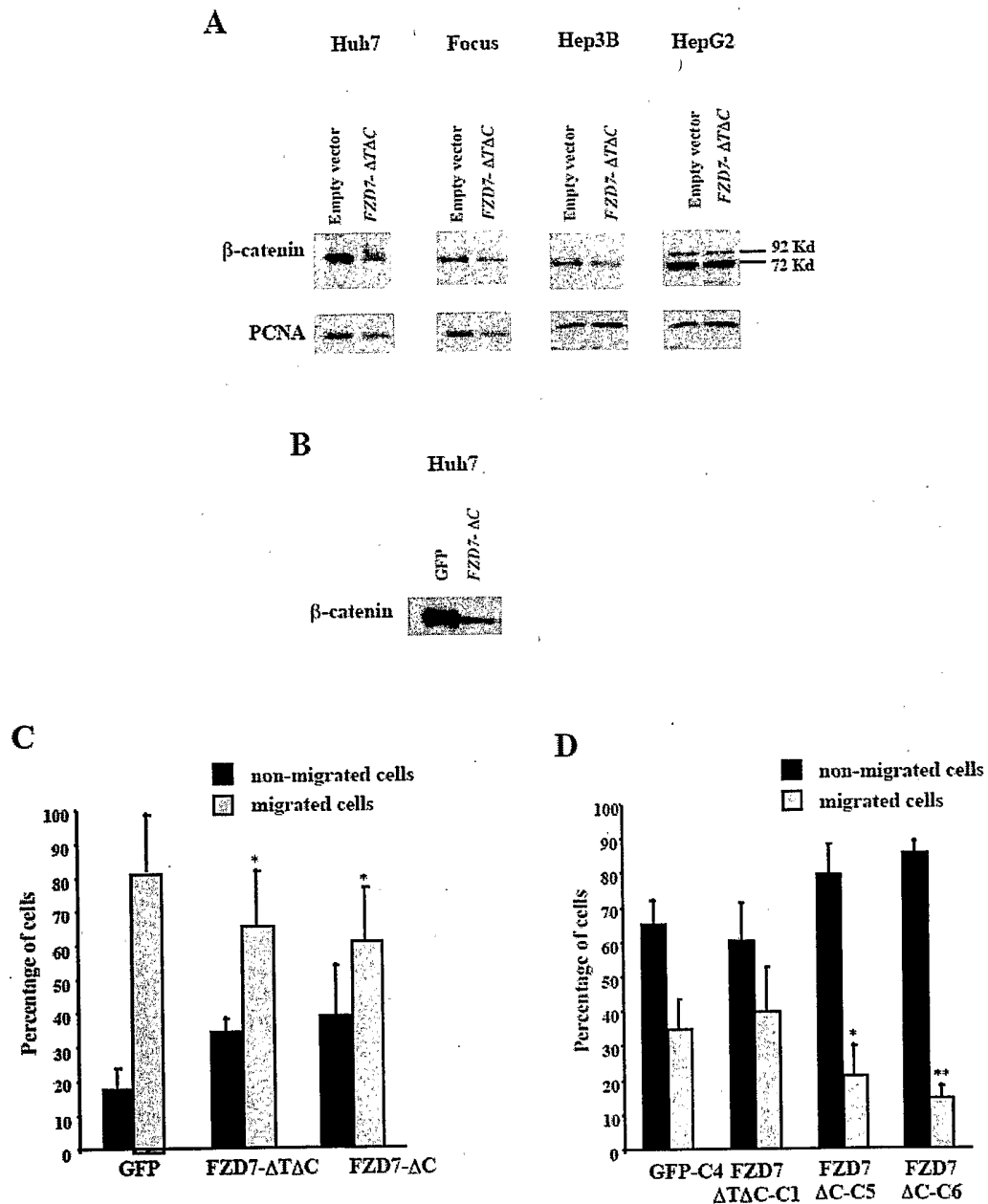
FIGS. 2A-2B



FIGS. 3A-3C

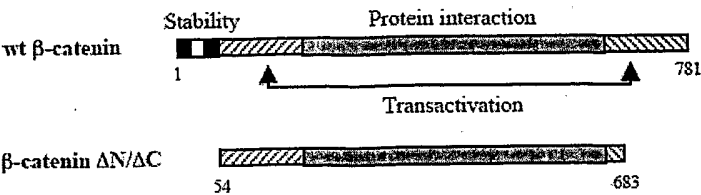


FIGS. 4A-4E

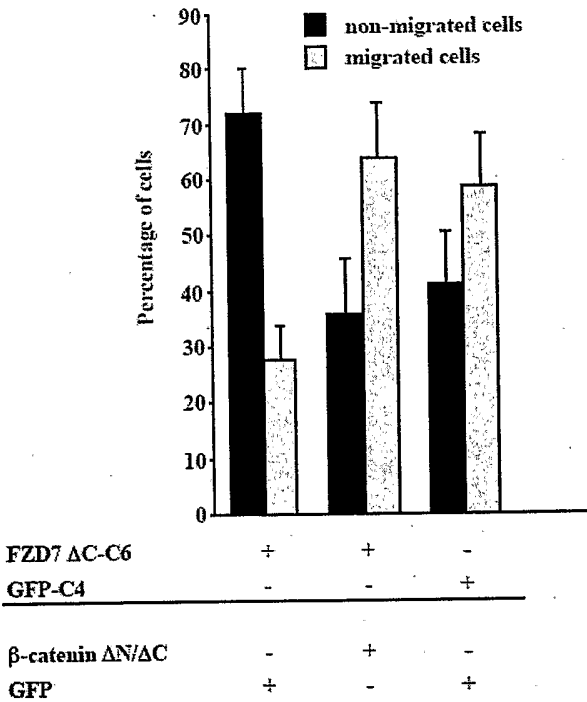


FIGS 5A-5D

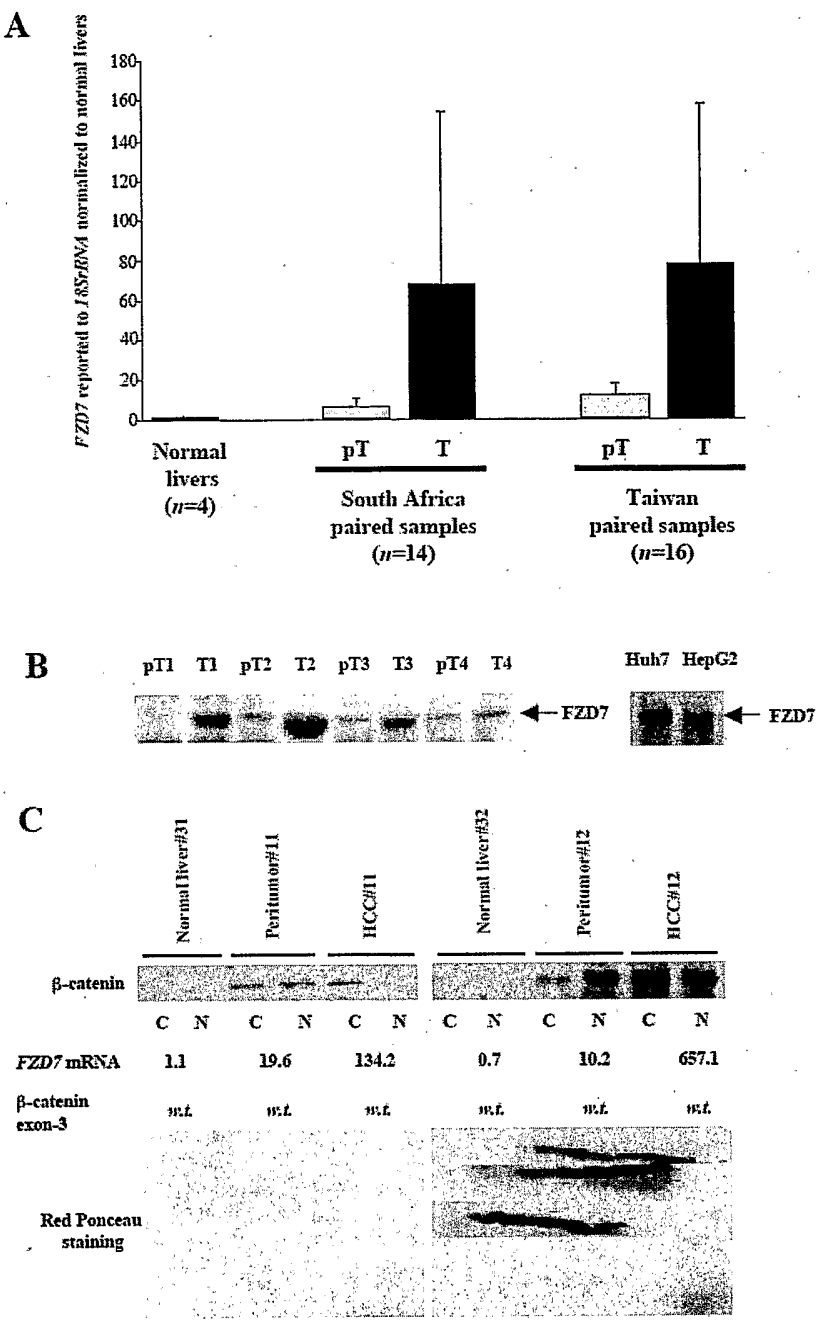
A



B



FIGS. 6A-6B



FIGS. 7A-7C

Human Frizzled 7

Accession: 075084

Protein name: Frizzled 7 [Precursor]

DEFINITION: frizzled 7; Frizzled, drosophila, homolog of, 7; frizzled(Drosophila) homolog 7 [Homo sapiens].

ACCESSION NP_003498

ORIGIN (574 aa)

MRDPGAAVPL SSLGFCALVL ALLGALSAGA GAQPYHGEKG ISVPDHGFCQ PISIPLECTDI
 AYNQTILPNL LGHTNQEDAG LEVHQFYPLV KVQCSPELRF FLCSMYAPVC TVLDQAIPPC
 RSLCERARQG CEALMNKFGF QWPERLRCEN FPHVGAGEIC VGQNTSDGSG GPGGGPTAYP
 TAPYLPDLPF TALPPGASDG KGRPAFPFSC PRQLKVPPYL GYRFLGERDC GAPCEPGRAN
 GLMYFKEEER RFARLWVGWV SVLCCASTLF TVLTYLVDMR RFSYPERPII FLSGCYFMVA
 VAHVAGFFLE DRAVCVERFS DDGYRTVAQG TKKEGCTILF MVLFFFGMAS SIWWVILSLT
 WFLAAGMKWG HEAIEANSQY PHLAAWAVPA VKTITILAMG QVDGDLNMGV CYVGFSSVDA
 LRGFVLAPLF VYFFIGTSFL LAGFVSFFRI RTIMKHDGK TEKLEKLMVR IGVFSVLYTV
 PATIVLACYF YEQAFAHWE RTWLLQTCKS YAVPCPPGHF PPMSPDFTVF MIKCLMTMIV
 GITTGFWIWS GKTLQSWRRF YHRLSHSSKG ETAV (SEQ ID NO:1)

Human Frizzled 7 Putative ligand binding site

* Cystein-rich domain (CRD)

CQPISIPLECTDIAYNQITILPNLLGHTNQEDAGLEVHQFYPLVKVQCSPELRFFLCSMYAPVCRSLCERARQ
GCEALMNKFGFQWPERLRCENFP (49-152) (SEQ ID NO:2)

Mouse Frizzled 7

Accession: Q61090

Protein name: Frizzled 7 [Precursor]

DEFINITION: frizzled 7 [Mus musculus].

ACCESSION NP_032083

ORIGIN (572 aa)

MRGPGTAASH SPLGLCALVL ALLGALPTDT RAQPYHGEKG ISVPDHGFCQ PISIPLECTDI
 AYNQTILPNL LGHTNQEDAG LEVHQFYPLV KVQCSPELRF FLCSMYAPVC TVLDQAIPPC
 RSLCERARQG CEALMNKFGF QWPERLRCEN FPHVGAGEIC VGQNTSDGSG GAGGSPTAYP
 TAPYLPDPPF TAMSPSDGRG RLSFPFSCPR QLKVPPYLG YRFLGERDCGA PCEPGRANGL
 MYFKEEERRF ARLWVGWVSV LSCASTLFTV LTYLVDMRRF SYPERPIIFL SGICYFMVAV
 HVAGFLLEDR AVCVERFSDD GYRTVAQGTK KEGCTILFMV LYFFFGMASSI WWVILSLTW
 LAAGMKWGHE AIEANSQYFH LAAWAVPAVK TITILAMGQV DGDLLSGVCY VGLSSVDALR
 GFVLAPLFVY LFIGTSFLA GFVSLFRIT IMKHDGKTE KLEKLMVRIG VFSVLYTVPA
 TIVLACYFYE QAFREHWERT WLLQTCKSYA VPCPPRHFSF MSPDFTVFMI KYLMTMIVGI
 TTGFWIWSGK TLQSWRRFYH RLSHSSKGET AV (SEQ ID NO:3)

FIG. 8A

Human Frizzled 8

Accession: Q9H461

Protein name: Frizzled 8 [Precursor]

Origin (694 aa)

```

MEWGYLLEVT SLLAALALLO RSSGAAAASA KELACQEITV PLCKGIGYNY TYMPNQFNHD
TQDEAGLEVH QFWPLVEIQC SPDLKFFLCS MYTPICLEDY KKPLPPCRSV CERAKAGCAP
LMRQYGFAPW DRMRCDRLPE QGNPDTLCMD YNRTDLTTAA PSPRRRLPPP PPGEQPPSGS
GHGRPPGARP PHRGGGRGGG GGDAAAPPAR GGGGGGKARP PGGAAPCEP GCQCRAPMVS
VSSERHPLYN RVKTGQIANC ALPCHNPFFS QDERAFTVFW IGLWSVLCFV STFATVSTFL
IDMERFKYPE RPIIFLSACY LFVSVGYLVR LVAGHEKVAC SGGAPGAGGA GGAGGAAAGA
GAAGAGAGGP GGRGEYEELG AVEQHVRVET TGPALCTVVF LLVYFFGMAS SIWWVILSLT
WFLAAGMKWG NEAIAGYSQY FHAAWLVPVS VKSI AVLALS SVDGDPVAGI CYVGNQSLDN
LRGFVLAPLV IYLFITMFL LAGFVSLFRI RSVIKQDGP TKTHKLEKLM IRLGLFTVLY
TVPAAVVVAC LFYEQHNRPR WEATHNCPCL RDLQPDQARR PDYAVFMLKY FMCLVVGITS
GVVWWSGKTL ESWSLCTRC CWASKGAAVG GGAGATAAGG GGGPGGGGGG GPGGGGGPGG
GGGSLYSDVS TGLTWRSCTA SSVSYPKOMP LSQV (SEQ ID NO:4)

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Human FZD8 Putative ligand binding site

* Cystein-rich domain (CRD)

CQEITVPLCKGIGYNYTYMPNQFNHDTQDEAGLEVHQFWPLVEIQCSPDLKFFLCSMYTPICLEDY
YKKPLPPCRSV CERAKAGCAPLMRQYGFAPWDRMRCDRLP (35-139) ((SEQ ID NO:5))

Mouse Frizzled 8

Accession: Q61091

Protein name: Frizzled 8 [Precursor]

Origin (685 aa)

```

MEWGYLLEVT SLLAALAVLQ RSSGAAAASA KELACQEITV PLCKGIGYNY TYMPNQFNHD
TQDEAGLEVH QFWPLVEIQC SPDLKFFLCS MYTPICLEDY KKPLPPCRSV CERAKAGCAP
LMRQYGFAPW DRMRCDRLPE QGNPDTLCMD YNRTDLTTAA PSPRRRLPPP PPPGEQPPSG
SGHSRPPGAR PPHRGGSSRG SGDAAPPS RGGKARPPG GAAPCEPGCQ CRAPMVS VSS
ERHPLYNRVK TGQIANCALP CHNPFFSQDE RAFTVFWIGL WSVLCFVSTF ATVSTFLIDM
ERFKYPERPI IFLSACYLFV SVGYLVRLVA GHEKVACSGG APGAGGRGGA GGAAAAGAGA
AGRGASSPGA RGEYEELGAV EQHVRYETTG PALCTVVFLL VYFFGMAS SI WWVILSLTW
LAAGMKWGNE AIAGYSQYFH LAWLVPVS VKSI AVLALSSV DGDVPVAGICY VGNQSLDNLR
GFVLAPLVIIY LFITMFLLA GFVSLFRIRS VIKQGGGPTK THKLEKLMIR LGLFTVLYTV
PAAVVVACLF YEQHNRPRWE ATHNCPCLRD LQPDQARRPD YAVFMLKYFM CLVVGITSGV
WVWSGKTLES WRALCTRCW ASKGAAVGAG AGGSGPGGSG GPGGGGGGHG GGGGSLYSDV
STGLTWRSCT ASSVSYPKQM PLSQV (SEQ ID NO:6)

```

FIG. 8B

Human Wnt3

Accession P56703

Protein name: Wnt-3 proto-oncogene protein [Precursor]

ACCESSION NP_110380

Definition: wingless-type MMTV integration site family, member 3; WNT-3 proto-oncogene protein precursor [Homo sapiens]

ORIGIN (355 aa)

MEPHLLGLLL GLLLGSTRVL AGYPIWWSLA LGQQYTSLGS QPLLCSIPG LVPKQLRFCR
 NYIEIMPSVA EGVKLG IQEC QHQFRGRRWN CTTIDDSLAI FGPVLDKATR ESAFVHAIAS
 AGVAFVTRTS CAEGTSTICG CDSHHKGPPG EGWKWGGCSE DADFGVLVSR EFADARENRP
 DARSAMNKHN NEAGRTTILD HMKLCKCHG LSGSCEVKTC WWAQPDFRAI GDFLKDKYDS
 ASEMVEKHR ESRGWVETLR AKYSLFKPPT ERDLVYYENS PNFCEPNPET GSFGTRDRTC
 NVTSHGIDGC DLLCCGRGHN TRTEKRKEC HCIFHWCCYV SCQECIRIYD VHTCK (SEQ ID
 NO:7)

Putative binding motifs**Human Wnt3**

* Secreted growth factor protein (motif or domain)

- 1) RESAFVHAIASAGVA (110-124) (SEQ ID NO:8)
- 2) RSACGTSTICGCD (129-142) (SEQ ID NO:9)
- 3) WKWGGCSEDADFG (153-165) (SEQ ID NO:10)
- 4) **CKCHGLSGSCEVKTCW (206-221)** (SEQ ID NO:11)
- 5) DLVYYENSPNFC (273-284) (SEQ ID NO:12)

Mouse Wnt3

Accession: P17553

Protein name: Wnt-3 proto-oncogene protein [Precursor]

DEFINITION:wingless-related MMTV integration site 3 [Mus musculus].

ACCESSION NP_033547

ORIGIN (355 aa)

MEPHLLGLLL GLLLSGTRVL AGYPIWWSLA LGQQYTSLAS QPLLCSIPG LVPKQLRFCR
 NYIEIMPSVA EGVKLG IQEC QHQFRGRRWN CTTIDDSLAI FGPVLDKATR ESAFVHAIAS
 AGVAFVTRTS CAEGTSTICG CDSHHKGPPG EGWKWGGCSE DADFGVLVSR EFADARENRP
 DARSAMNKHN NEAGRTTILD HMKLCKCHG LSGSCEVKTC WWAQPDFRAI GDFLKDKYDS
 ASEMVEKHR ESRGWVETLR AKYALFKPPT ERDLVYYENS PNFCEPNPET GSFGTRDRTC
 NVTSHGIDGC DLLCCGRGHN TRTEKRKEC HCVFHWCCYV SCQECIRIYD VHTCK (SEQ ID
 NO:13)

FIG. 8C

Human Wnt8B

Accession: Q93098

Protein name: Wnt-8b protein [Precursor]

DEFINITION: wingless-type MMTV integration site family, member 8B precursor [Homo sapiens].

ACCESSION: NP_003384

ORIGIN (351 aa)

MFLSKPSVYI CLFTCVLQLS HSWSVNNFLM TGPKAYLIYS SSVAAGAQSG IEECKYQFAW
 DRWNCPERAL QLSSHGGLRS ANRETAFVHA ISSAGVMYTL TRNCSLGDFD NCGCDDSRNG
 QLGGQGWLWG GCSDNVGFGE AISKQFVDAL ETGQDARAAM NLHNNEAGRK AVKGTMKRTC
 KCHGVSGSCT TQTCWLQLPE FREVGAHLKE KYHAALKVDL LQGAGNSAAA RGAIADTFRS
 ISTRELVHLE DSPDYCLENK TLGLLGTEGR ECLRRGRALG RWELRSCRRL CGDCGLAVEE
 RRAETVSSCN CKFWHCCA VR CEQRRRVTK YFCSRAERPR GGAHKPGRK P (SEQ ID NO:14)

Putative binding motifsHuman Wnt8b

* Secreted growth factor protein (motif or domain)

- 1) RETAFVHAISSAGVM (83-97) (SEQ ID NO:15)
- 2) RNCSLGDFDNCGCD (102-115) (SEQ ID NO:16)
- 3) WLWGGCSDNVGFG (127-139) (SEQ ID NO:17)
- 4) **CKCHGVSGSCTTQTCW (180-195)** (SEQ ID NO:18)
- 5) ELVHLEDSPDYC (245-256) (SEQ ID NO:19)

Mouse Wnt8B

Accession: Q9WUD6

Protein name: Wnt-8b protein [Precursor]

DEFINITION: wingless related MMTV integration site 8b [Mus musculus].

ACCESSION NP_035850

ORIGIN (350 aa)

MFLMKPVCVL LVTVCVLRSH AWSVNNFLMT GPKAYLVYSS SVAAGAQSGI EECKYQFAWD
 RWNCPERALQ LSSHGGLRSA NRETAFVHAI SSAGVMYTLT RNCSLGDFDN CGCDDSRNGQ
 LGGQGWLWGG CSDNVGFGEA ISKQFVDALE TGQDARAAMN LHNNEAGRKA VKGTMKRTCK
 CHGVSGSCTT QTCWLQLPEF REVGAHLKEK YHAALKVDLL QGAGNSAAGR GAIADTFRSI
 STRELVHLED SPDYCLENKT LGLLGTEGRE CLRRGRALGR WERRSCRRLC GDCGLAVEER
 RAETVSSCNC KFWHCCA VR EQRRRVTKY FCSRAERPPR GAAHKPGKNS (SEQ ID NO:20)

FIG. 8D

Human Wnt 11

Accession: O96014

Protein name: Wnt-11 protein [Precursor]

DEFINITION: wingless-type MMTV integration site family,
member 11 precursor [Homo sapiens]

ACCESSION NP_004617

ORIGIN (354 aa)

MRARPQVCEA LLFALALQTG VCYGIKWLAL SKTPSALALN QTQHCKQLEG LVSAQVQLCR
 SNLELMHTV HAAREVMKAC RRAFADMRWN CSSIELAPNY LLDLERGTRE SAFVYALSAA
 AISHAIARAC TSGDLPGCSC GPVPGEPGP GNRWGGCADN LSYGLLMGAK FSDAPMKVKK
 TGSQANKLMR LHNSEVGRQA LRASLEMKCK CHGVSGSCSI RTCWKGLQEL QDVAADLKTR
 YLSATKVVHR PMGTRKHLVP KDLDIRPVKD SELVYLQSSP DFCMKNEKVG SHGTQDRQCN
 KTSNGSDSCD LMCCGRGYNP YTDRVVERCH CKYHWCCYVT CRRCERTVER YVCK (SEQ ID
 NO:21)

Putative binding motifs**Human Wnt11**

* Secreted growth factor protein (motif or domain)

- 1) RESAFVYALSAAIS (109-123) (SEQ ID NO:22)
- 2) RACTSGDLPGCSCG (128-141) (SEQ ID NO:23)
- 3) NRWGGCADNLSYG (152-164) (SEQ ID NO:24)
- 4) **CKCHGVSGSCSIRTCW (209-224)** (SEQ ID NO:25)
- 5) ELVYLQSSPDFC (272-283) (SEQ ID NO:26)

Mouse Wnt 11

Accession: P48615

Protein name: Wnt-11 protein [Precursor]

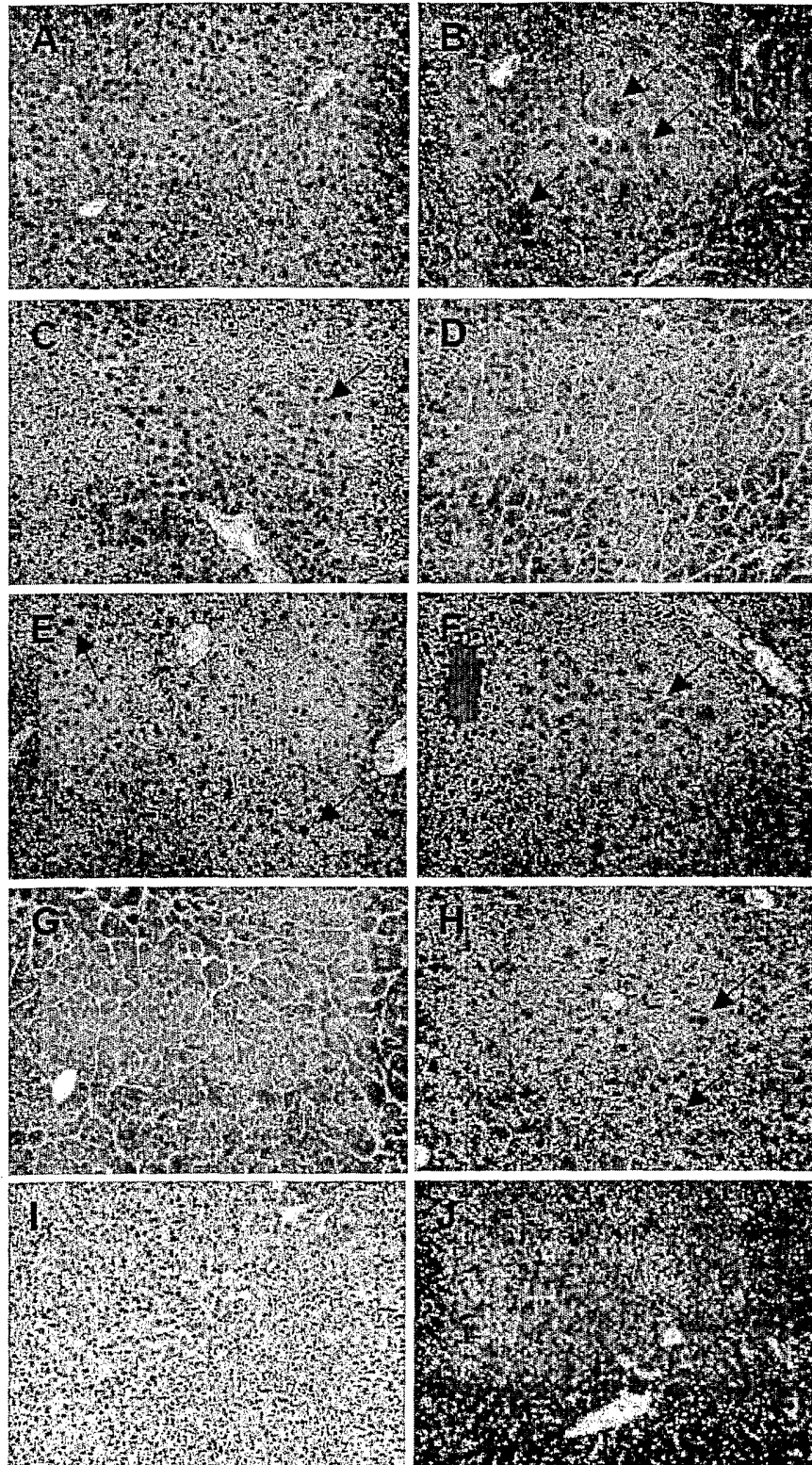
DEFINITION: wingless-related MMTV integration site 11 [Mus
musculus].

ACCESSION NP_033545

ORIGIN (354 aa)

MRARPQVCEA LLFALALHTG VCYGIKWLAL SKTPAALALN QTQHCKQLEG LVSAQVQLCR
 SNLELMRTIV HAARGAMKAC RRAFADMRWN CSSIELAPNY LLDLERGTRE SAFVYALSAA
 TISHTIARAC TSGDLPGCSC GPVPGEPGP GNRWGGCADN LSYGLLMGAK FSDAPMKVKK
 TGSQANKLMR LHNSEVGRQA LRASLETCKCK CHGVSGSCSI RTCWKGLQEL QDVAADLKTR
 YLSATKVVHR PMGTRKHLVP KDLDIRPVKD SELVYLQSSP DFCMKNEKVG SHGTQDRQCN
 KTSNGSDSCD LMCCGRGYNP YTDRVVERCH CKYHWCCYVT CRRCERTVER YVCK (SEQ ID
 NO:27)

FIG. 8E



FIGS. 9A-9J

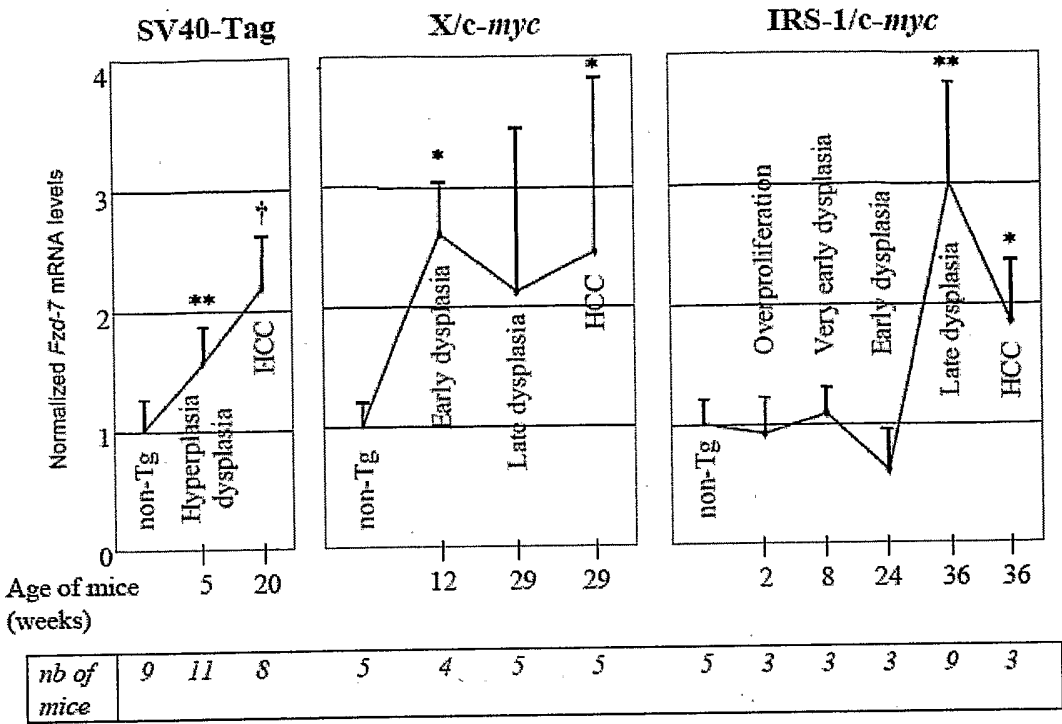
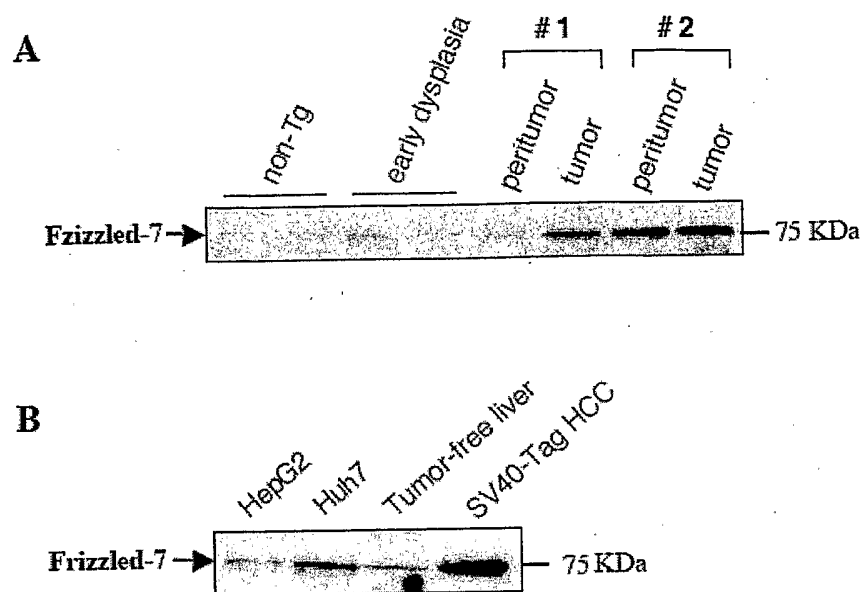


FIG. 11



FIGS. 12A-12B

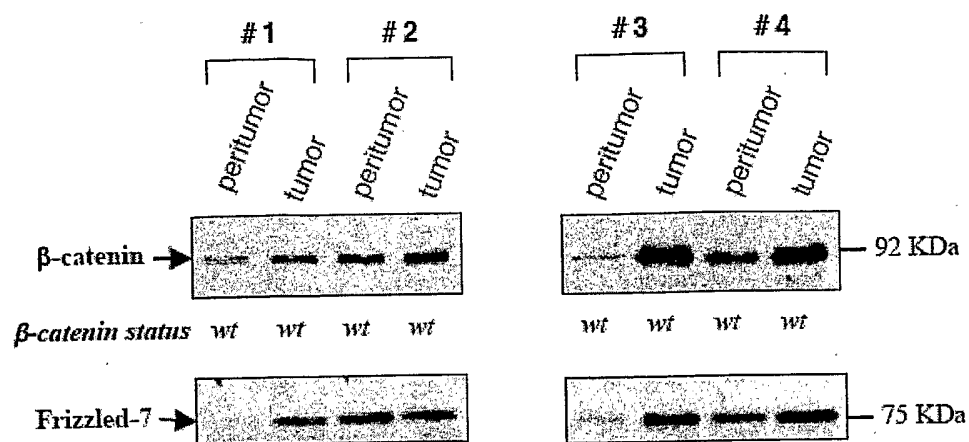
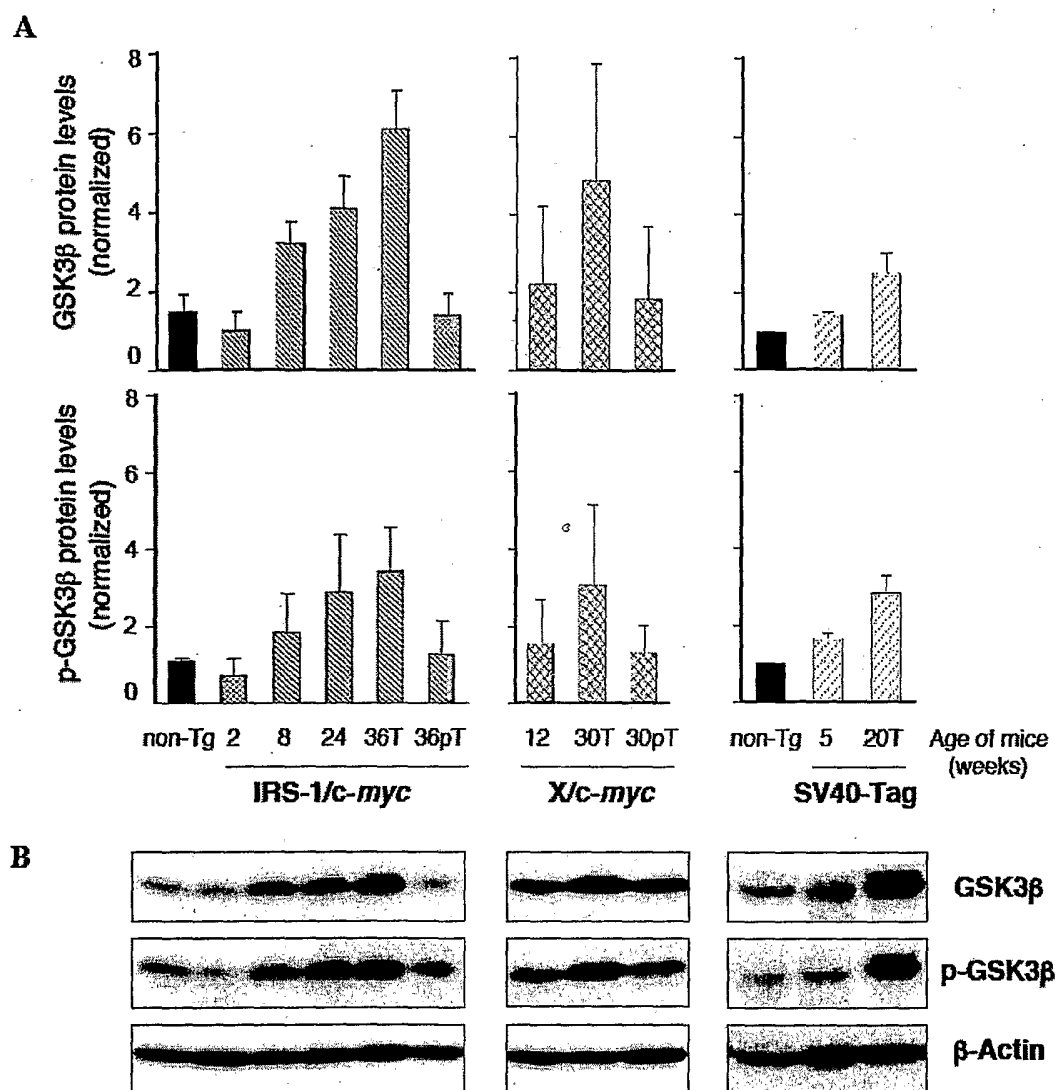


FIG. 13



FIGS. 14A-14B

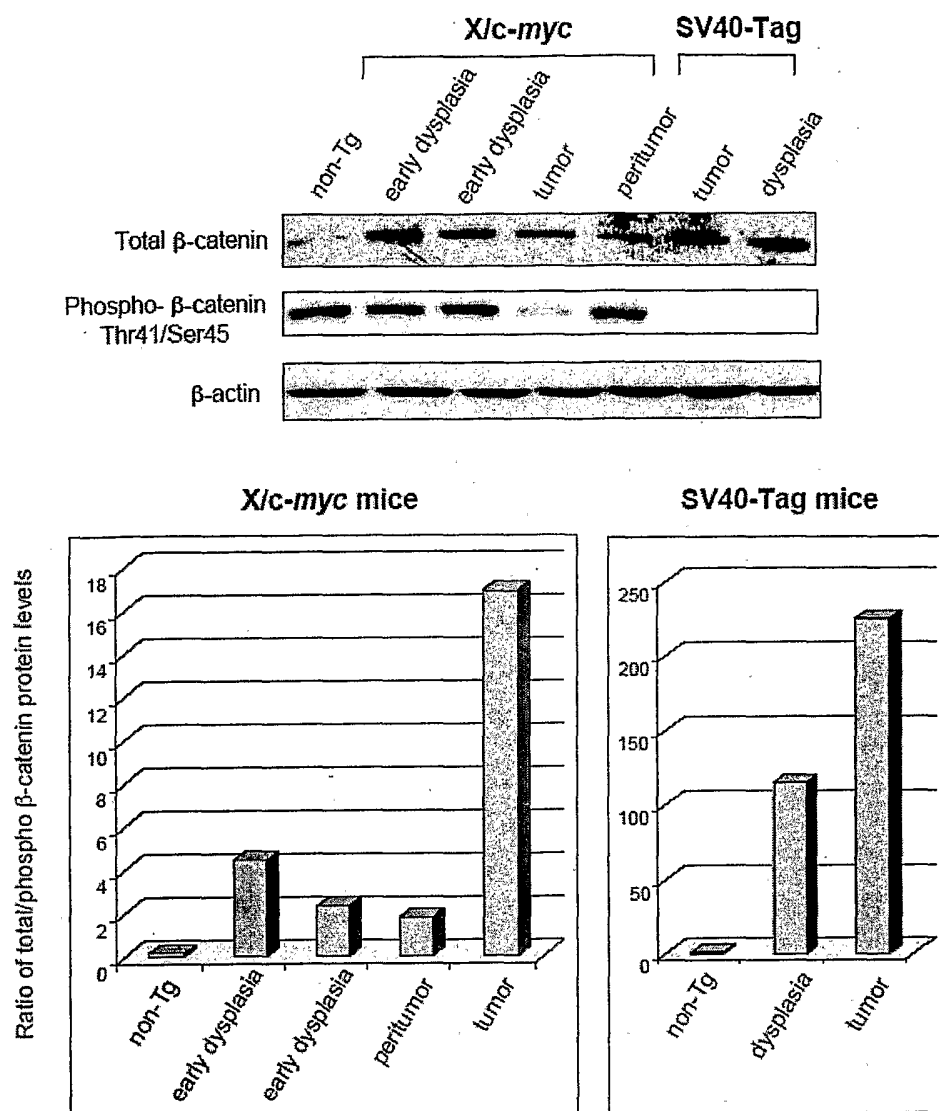


FIG. 15