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Review article

Tumor biology

Wnt pathways in focus – mapping current clinical trials across the cancer spectrum

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The Wnt pathway has a pivotal function in tissue development and homeostasis, overseeing cell growth or differentiation. Aberrant Wnt signalling pathways have been associated with the pathogenesis of diverse malignancies, influencing cell proliferation, differentiation, cancer stem cell renewal, the tumour microenvironment and thereby significantly impacting tumour development and therapeutic responsiveness. Promisingly, current research underscores the potential therapeutic value of targeting Wnt pathways, particularly canonical Wnt/β-catenin signalling, in the context of numerous cancer types. Key constituents of the Wnt pathway, such as the Wnt/receptor, β-catenin degradation or transcription complexes, have been focal points for interventions in preclinical studies. To comprehend potential therapeutic strategies, we conduct an analysis of ongoing clinical trials that specifically aim to target components of the Wnt pathways across a diverse spectrum of cancer types. By scrutinizing these trials, including their respective phases, targeted patient populations ,and observed outcomes, this review provides a consolidated overview of the current translational landscape of Wnt-targeted therapies, thus offering a roadmap for future research endeavours.

Key words: cancer, clinical trials, Wnt signalling pathways, targeted therapy

Introduction

Cancer is one of the main causes of death worldwide [1]. While chemotherapy remains the backbone of systemic treatment for both the radically and palliatively treated cancer patient population, new options including a growing number of molecularly targeted drugs have entered the market with new and new indications [2]. The journey from the initial discovery of a compound to its approval by regulatory bodies like the Food and Drug Administration (FDA) or the European Medicines Agency (EMA) is an extensive process. It initiates with preclinical evaluations and advances through a multi-stage series of clinical trials involving human subjects. A significant proportion of compounds displaying promise in the preclinical phase ultimately do not achieve the specified endpoints during the clinical trial phases [3–6]. Figure 1 succinctly outlines this intricate progression.

There are numerous signaling pathways abrupted in cancer cells that have been already used as targets for different therapeutic strategies including kinase inhibitors (Kis), monoclonal antibodies (mAbs), antibody-drug conjugates (ADCs), drugs' nanoforms [2]. Activation of these pathways can induce

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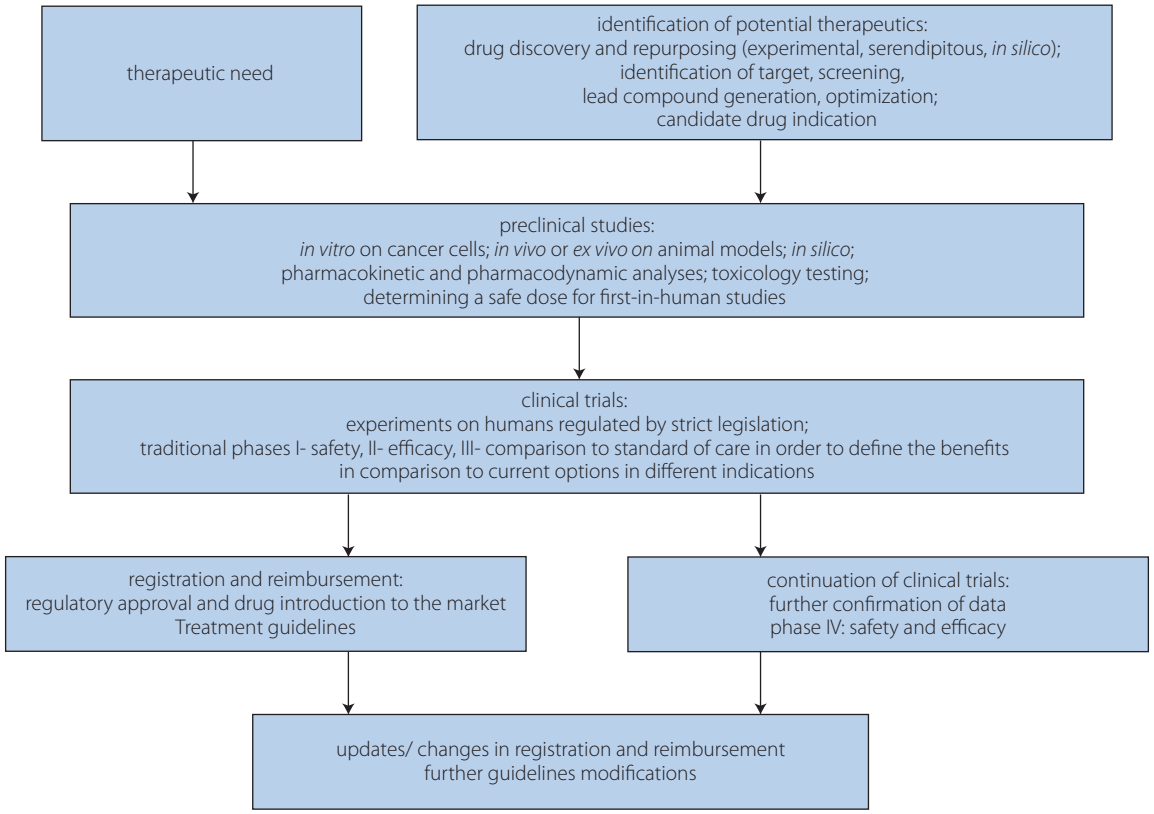

Figure 1. Sequential stages of drug discovery and registration [3–6]

alterations in cell survival capabilities, metabolic processes, cellular proliferation, differentiation, thereby impacting the tumor microenvironment. Moreover, it plays a role in angiogenesis, epithelial to mesenchymal transition, and the formation of metastases [7–10]. Among the numerous pathways with key components that are established targets for treatment, prominent examples comprise epidermal growth factor receptor/RAS/rapidly accelerated fibrosarcoma/mitogen-activated protein kinase (EGFR/RAS/RAF), human epidermal growth factor receptor 2 (HER2), sonic hedgehog (SHH), vascular endothelial growth factor receptor (VEGFR), platelet-derived growth factor receptor (PDGFR), and protein kinase B/mammalian target of rapamycin (AKT/mTOR). It is noteworthy that the elements of these pathways often intersect during signal transduction [7–10]. Wnt represents a fundamental pathway crucial in both embryonic development and the onset of tumorigenesis [11]. Presently, there are no registered drugs specifically targeting the elements of this pathway, despite it presenting an apparent target for innovative anticancer agents. The objective of this review is to delve into the prospects of translating elements of the Wnt pathway from preclinical research to clinical applications. Through meticulous examination of these trials, encompassing their phases, targeted population, and the active drug studied, the review furnishes a comprehensive summary of the present translational panorama concerning therapies directed at the Wnt pathways.

Canonical and non-canonical Wnt signalling

The Wnt pathway plays a pivotal role in numerous developmental and homeostatic processes. Aberrations within this pathway have been implicated in a spectrum of pathological conditions, including cancers. The intricate balance and regulation of the Wnt pathway underscore its paramount importance in cellular homeostasis, presenting a potential target for therapeutic interventions in malignancies and other diseases.

There are in fact several signaling pathways that can be activated with the elements of Wnt. The canonical pathway is the most well-known (fig. 2). At the core of this pathway lies β-catenin, a key protein acting as a linchpin orchestrating downstream signaling events. Two other pathways are planar cell polarity (PCP) and calcium-related pathways [11–16].

Wnt proteins are categorized into canonical and noncanonical types, instigating both respective pathways by engaging Frizzled (FZD) receptors (tab. I). Frizzled receptors require a co-receptor, low-density lipoprotein receptor-related protein 5/6 (LRP5/6) for canonical signaling, and receptor tyrosine kinase-like orphan receptor 1/2 (ROR1/2) for non-canonical signaling, to transmit signals effectively [11–17].

Within the canonical pathway, upon activation, Wnt binding disrupts the β-catenin destruction complex, preventing the phosphorylation of β-catenin by GSK-3β, thereby averting its proteasomal degradation. Key components of the destruction complex include:

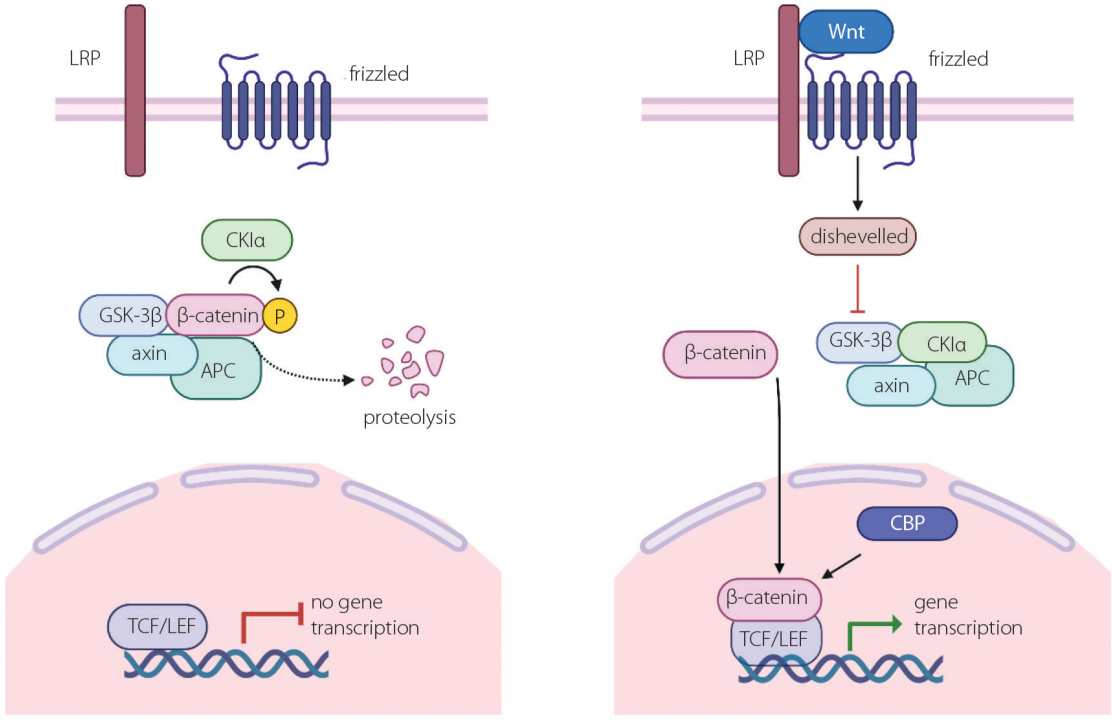

Figure 2. Canonical Wnt pathway inactive (on the left-hand side) and active (on the right-hand side) (created with BioRender) [11–16] APC – *adenomatous polyposis coli*; CBP – CREB-binding protein; CK1-α – casein kinase 1-alpha; GSK-3β – glycogen synthase kinase 3-beta; LEF – lymphoid enhancer factor; LRP – low-density lipoprotein receptor-related protein; TCF – T cell factor

Table I. Canonical and non-canonical elements of the Wnt family [11, 16]

Pathway		Proteins
canonical	Wnt / β-catenin	Wnt1, Wnt2, Wnt3, Wnt3a, Wnt8a, Wnt8b, Wnt10a, Wnt10b
non canonical	PCP, Wnt / Ca^{2+}	Wnt3, Wnt4, Wnt5a, Wnt5b, Wnt6, Wnt7a, Wnt7b, Wnt11

PCP – planar-cell polarity

- *adenomatous polyposis coli* (APC),
- glycogen synthase kinase 3-beta (GSK-3β),
- axin, casein kinase 1-alpha (CK1-α).

The accumulation of β-catenin in the cytoplasm enables its translocation into the nucleus, where it forms complexes with various transcription factors, primarily lymphoid enhancer factor/T-cell factor (LEF/TCF), initiating the transcription of vital Wnt/β-catenin target genes such as: cMyc, cyclin D1 (CCND1), and VEGF or programmed death-ligand 1 (PD-L1) [11–16].

Non-canonical Wnt pathways are Wnt / PCP and Wnt-cyclic guanosine monophosphate / calcium ion (Wnt-cGMP/Ca^{2+}) signaling. The targets for these non-canonical pathways can include matrix metalloproteinases (MMPs) or AKT/mTOR. These pathways are believed to exert an influence on processes such as epithelial-mesenchymal transition (EMT), cell migration, cell metabolism, chemo-resistance, or the formation of metastases [11, 16, 17].

Preclinical and clinical cancer studies regarding Wnt elements

Inhibition of the Wnt pathway represents an interesting and promising molecular target for novel anticancer therapies in various malignancies. Many new molecules have been investigated in preclinical studies or in clinical trials – mainly phase 1 (tab. II). Some of them have reached phase 2 clinical trials in the treatment of solid malignancies, as well as hematologic, but recruitment is ongoing or the results of those trials are expected to be soon published. An interesting approach represents the combination of Wnt inhibitors with chemotherapy of targeted therapies – PD-1/PD-L1 inhibitors (nivolumab / pembrolizumab) or EGFR inhibitors (cetuximab).

Katoh and Katoh divided Wnt-targeted agents into pan-Wnt inhibitors (like porcupine inhibitors), canonical (like β-catenin protein-protein inhibitor) and non-canonical (like ROR1 inhibitors) [12]. However, there is a significant group of compounds that modulate the signal indirectly or influence

Table II. Agents inhibiting the Wnt pathway which are under investigation. Complied on the basis of clinicaltrials.gov as of April 2023, unless otherwise specified

Name of agent	Mechanism of action	Development stage	Indications	Reference
PKF115–584, CGP049090, PKF222–815, PKF118–310, PKF118–744, ZTM000990	β-catenin – TCF antagonists	preclinical	colorectal cancer, breast cancer	[18, 19]
iCRT3, iCRT5, iCRT14	β-catenin – TCF antagonists	preclinical	colorectal cancer, triple negative breast cancer	[20, 21]
BC21	β-catenin – TCF antagonists	preclinical	colorectal cancer	[22]
FH535	β-catenin – TCF antagonists	preclinical	triple negative breast cancer, colorectal cancer, lung cancer, hepatocellular carcinoma	[23, 24]
CWP232228	β-catenin – TCF antagonists	preclinical	breast cancer	[25]
ICG-001	β-catenin / CBP inhibitor	preclinical	triple negative breast cancer	[26]
CG0009	glycogen synthase kinase 3α/β inhibitor	preclinical	breast cancer	[27]
niclosamide	inhibition the binding of a WNT ligand to LRP5/6 receptors	preclinical	breast cancer	[28]
salinomycin	inhibition the binding of a WNT ligand to LRP5/6 receptors	preclinical	breast cancer, prostate cancer, chronic lymphocytic leukemia	[29, 30]
LGK974 (WNT974)	inhibitor of the WNT-receptor complex (porcupine inhibitor)	phase 1 clinical trial, recruiting	pancreatic cancer, BRAF-mutant colorectal cancer, melanoma, triple negative breast cancer, head and neck squamous-cell cancer, cervical squamous-cell cancer, esophageal squamous-cell cancer, lung squamous-cell cancer	[31]
		phase 1 and 2 clinical trial + cetuximab, completed	BRAF-mutant metastatic colorectal cancer	[32]
		preclinical	Ewing sarcoma	[33]
		preclinical	clear cell, renal cell carcinoma	[34]
ETC-1922159	inhibitor of the WNT-receptor complex (porcupine inhibitor)	phase I clinical trial +/– pembrolizumab, recruiting	advanced solid tumors	[35]
CGX1321	Inhibitor of the WNT-receptor complex (porcupine inhibitor)	phase I clinical trial +/– pembrolizumab or encorafenib + cetuximab, recruiting	advanced gastrointestinal tumors	[36]
		phase 1 clinical trial, recruiting	advanced gastrointestinal tumors	[37]
RXC004	inhibitor of the WNT-receptor complex (porcupine inhibitor)	phase 1 clinical trial +/– nivolumab, recruiting	advanced solid tumors	[38]
		phase 2 clinical trial, recruiting	advanced solid tumors	[39]
		phase 2 clinical trial +/– nivolumab, recruiting	colorectal cancer	[40]
XNW7201	inhibitor of the WNT-receptor complex (porcupine inhibitor)	phase 1 clinical trial, active, not recruiting	advanced solid tumors	[41]
OMP-18R5 (vantictumab)	inhibitor of the WNT-receptor complex (antibody against WNT family proteins – namely FZD1, FZD2, FZD5, FZD7 and FZD8)	phase 1 clinical trial, completed	advanced solid tumors	[42]
		phase 1 clinical trial +/– nab-paklitaxel and gemcitabine, completed	advanced pancreatic cancer	[43, 44]
		phase 1b clinical trial + docetaxel, completed	non-small cell lung cancer	[45]
		phase 1b clinical trial, completed	metastatic breast cancer	[46]

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Table II cont. Agents inhibiting the Wnt pathway which are under investigation. Complied on the basis of clinicaltrials.gov as of April 2023, unless otherwise specified

Name of agent	Mechanism of action	Development stage	Indications	Reference
OMP-54F28 (ipafricept)	inhibitor of the WNT-receptor complex (antibody against WNT family proteins – namely FZD 8 receptor)	phase 1 clinical trial, completed	advanced solid tumors	[47, 48]
		phase 1 clinical trial + sorafenib, completed	hepatocellular cancer	[49]
		phase 1 clinical trial + paclitaxel and carboplatin, completed	ovarian cancer	[50, 51]
		phase 1 clinical trial + nab-paclitaxel and gemcitabine, completed	pancreatic cancer	[52]
OTSA101	inhibitor of the WNT-receptor complex (antibody against Wnt family proteins – namely FZD 10 receptor)	phase 1 clinical trial, recruiting	synovial sarcoma	[53]
NVP-TNKS656	β-catenin-destruction complex inhibitors, namely tankyrase inhibitors (PARPs family)	preclinical	colorectal cancer	[54]
XAV939	β-catenin-destruction complex inhibitors, namely tankyrase inhibitors (PARPs family)	preclinical	breast cancer	[55]
PRI-724	inhibition of the CBP and β-catenin interaction	phase 1a/1b clinical trial, terminated	advanced solid tumors	[56, 57]
		phase 1 clinical trial + gemcitabine, completed	pancreatic cancer	[58, 59]
		phase 1 and 2 clinical trial, completed	acute myeloid leukemia, chronic myeloid leukemia	[60]
CWP232291	inhibitor of the Wnt pathway, induction of apoptosis *via* activation of caspases	phase 1 clinical trial, completed	refractory acute myeloid leukemia, chronic myelomonocytic leukemia, myelodysplastic syndrome, myelofibrosis	[61, 62]
		phase 1 clinical trial +/– lenalidomide, dexamethasone, completed	multiple myeloma	[63, 64]
		phase 1 and 2 clinical trial, active, not recruiting	acute myeloid leukemia	[65]
DKN-01	monoclonal antibody, inhibitor of the DKK1 activity, a modulator of Wnt / β-catenin signaling	phase 1 clinical trial +/– paclitaxel or pembrolizumab, completed	esophageal cancer gastroesophageal junction cancer, gastric adenocarcinoma with Wnt signaling alterations	[66, 67]
		phase 1 clinical trial + gemcitabine/cisplatine, completed	carcinoma primary to the intra- or exta-hepatic biliary system or gallbladder	[68, 69]
		phase 1b/2a clinical trial +/– docetaxel, recruiting	prostate cancer	[70, 71]
		phase 1 and 2 clinical trial +/– sorafenib, recruiting	advanced liver cancer	[72]
		phase 2 clinical trial + nivolumab, recruiting	advanced biliary tract cancer	[73]
		phase 2 clinical trial +/– paclitaxel, completed	endometrial cancer, uterine cancer, ovarian cancer, carcinosarcoma	[74]
		phase 2 clinical trial + tiselizumab +/– chemotherapy, recruiting	gastric cancer, gastroesophageal cancer	[75]
		phase 1 clinical trial, completed	multiple myeloma, solid tumors, non-small-cell lung cancer	[76, 77]
		phase 1 clinical trial + lenalidomide/dexamethasone, completed	relapsed or refractory multiple myeloma	[77]
		phase 1 and 2 clinical trial + atezolizumab, recruiting	metastatic esophageal cancer, metastatic gastric cancer	[78]

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Table II cont. Agents inhibiting the Wnt pathway which are under investigation. Complied on the basis of clinicaltrials.gov as of April 2023, unless otherwise specified

Name of agent	Mechanism of action	Development stage	Indications	Reference
Foxy-5	WNT5A-mimicking peptide	phase 1 clinical trials, completed	breast cancer, colon cancer, prostate cancer	[79, 80]
		phase 2 clinical trial, recruiting	colon cancer (neoadjuvant setting)	[81]
UC-961 (cirmtuzumab)	monoclonal antibody against ROR1 of the non-canonical Wnt pathway	phase 2 clinical trial + docetaxel, not yet recruiting	metastatic castration resistant prostate cancer	[82]
		phase 1 clinical trial, completed	relapsed or refractory chronic lymphocytic leukemia	[83, 84]
		phase 1 and 2 clinical trial + ibrutinib, active, not recruiting	B-cell lymphoid malignancies	[85, 86]
		phase 2 clinical trial, recruiting	chronic lymphocytic leukemia, consolidation after venetoclaxs	[87]
		phase 1 clinical trial + paclitaxel, active, not recruiting	breast cancer	[88]
PRI-724	CBP / β-catenin antagonist	phase 2 clinical trial + FOLFOX and bevacizumab, withdrawn	metastatic colorectal cancer	[89]
		phase 1 clinical trial + gemcitabine, completed	advanced pancreatic cancer	[90, 91]
		phase 1 and 2 clinical trial, completed	acute myeloid leukemia, chronic myeloid leukemia	[92]
		phase 1 clinical trial, terminated	advanced solid tumors	[93]
PF-06647020 (cofetuzumab pelidotin)	monoclonal antibody against PTK7 – inhibition of non-canonical Wnt pathway	phase 1 clinical trial + gedatolisib, completed	triple negative breast cancer	[94–96]
		phase 1 clinical trial, completed	non-small cell lung cancer	[97, 98]
		phase 1 clinical trial, completed	advanced solid tumors	[99, 100]
GDC-0449 (vismodegib)	inhibitor of the hedgehog pathway	FDA and EMA registered	metastatic/locally advanced basal cell carcinoma	[101, 102]
		numerous clinical trials phase 1–3	advanced solid tumors (also advanced breast cancer) hematologic malignancies	#
LDE225 (sonidegib)	inhibitor of the hedgehog pathway	FDA and EMA registered	metastatic/locally advanced basal cell carcinoma	[103, 104]
		numerous clinical trials phase 1–3	advanced solid tumors (also advanced breast cancer) hematologic malignancies	#
itraconazole	antifungal medication, inhibitor of the hedgehog pathway	numerous clinical trials phase 1–3	prostate cancer, lung cancer, ovarian cancer, esophageal cancer, multiple myeloma, solid malignancies	#
PF-04449913 (glasdegib)	inhibitor of the hedgehog pathway	phase 1 and 2 clinical trials	hematologic malignancies	#
		phase 1 clinical trial, completed	solid tumors	[105, 106]
		phase 1 and 2 clinical trial + temozolomide, active, not recruiting	glioblastoma	[107]
IPI-926 (patidegib)	inhibitor of the hedgehog pathway	phase 1 clinical trial, completed	basal cell carcinoma	[108]
		phase 1 and 2 clinical trial + gemcitabine, completed	pancreatic cancer	[109, 110]
		phase 1 + FOLIFIRINOX, completed	pancreatic cancer	[111, 112]
		phase 1 clinical trial, completed	solid tumor malignancies	[113, 114]
		phase 1 clinical trial + cetuximab, completed	head and neck cancer	[115, 116]
		phase 2 clinical trial, completed	unresectable chondrosarcoma	[117]
LY2940680	inhibitor of the hedgehog pathway	phase 2 clinical trial, completed	solid tumor malignancies	[118]

Table II cont. Agents inhibiting the Wnt pathway which are under investigation. Complied on the basis of clinicaltrials.gov as of April 2023, unless otherwise specified

Name of agent	Mechanism of action	Development stage	Indications	Reference
ENV-101	inhibitor of the hedgehog pathway	phase 2 clinical trial, recruiting	advanced solid tumors harboring PTCH1 loss of function mutations	[119]
		phase 1 clinical trial, completed	breast cancer, colon cancer, cholangiocarcinoma, soft tissue sarcoma	[120]
		phase 1 and 2 clinical trial, completed	esophageal or gastroesophageal junction cancer	[121]
lycopene	naturally synthesized carotenoid (an active component of red fruits and vegetables) – suppression of β-catenin nuclear expression	phase 2 clinical trial, active, not recruiting	skin toxicity in patients with colorectal carcinoma treated with panitumumab	[122]
		preclinical	gastric cancer, breast cancer	[123, 124]
artesunate	antimalarial drug – suppression of Wnt pathway by downregulation of c-Myc and cyclin D1	phase 2 clinical trial, active, not recruiting	stage II/III colorectal cancer (pre-operative treatment)	[125, 126]
		phase 1 clinical trial, completed	advanced solid tumors	[127, 128]
		phase 1 clinical trial, completed	metastatic breast cancer	[129, 130]
resveratol	non-flavonoid polyphenol – suppression of Wnt pathway by decreasing the expression of β-catenin and cyclin D1	phase 1 clinical trial, completed	colon cancer	[131, 132]
		preclinical	breast cancer, gastric cancer	[133, 134]
quercetin	flavonoid (component of onion, red grapes, lettuce, tomato). Inhibition of the Notch1, PI3K/AKT and β-catenin signaling pathways	preclinical	breast cancer, ovarian cancer, B-cell lymphomas	[135–137]

CBP – CREB-binding protein; BRAF – B-Raf proto-oncogene, serine/threonine kinase; DKK1 – dickkopf-1 protein; EMA – European Medical Agency; FDA – Food and Drug Administration; FOLFOX – folinic acid, 5-fluorouracil and oxaliplatin; FOLFIRINOX – folinic acid, 5-fluorouracil, irinotecan and oxaliplatin; FZD – frizzled receptor; LRP5/6 – low-density lipoprotein receptor-related protein 5/6; PARPs – poly (ADP-ribose) polymerases; PI3K/AKT – phosphoinositide 3-kinase/protein kinase B; PTK7 – protein tyrosine kinase 7; TCF – T cell factor; # – for details see clinicaltrials.gov

Wnt signalling by interfering with other pathways (like SHH). β-catenin itself plays an important role as a signal transducer in other pathways including trophoblast cell surface antigen 2 (TROP-2) [138].

Current trials, as shown in table II, involve drugs acting on numerous levels of these signaling pathways:

- Outside the cancer cell / on the cell membrane level: Wnt--mimicking agents [79, 80]; monoclonal antibody against ROR1 (cirmtuzumab) [82–86]; Wnt proteins / receptors inhibitors like: porcupine inhibitors LGK974, ETC-1922159, CGX1321, RXC004, XNW7201 [31–41] or FZD inhibitors (vantictumab, ipafricept, OTSA101) [42–53]. Porcupine serves as a vital enzyme within the Wnt signaling pathway, aiding in the palmitoylation of Wnt proteins. This alteration is pivotal for the appropriate secretion of Wnt proteins and the initiation of the Wnt signaling pathway [139]. Monoclonal antibodies against protein tyrosine kinase 7 (PTK7) can also be included into that group. PTK-7 is a transmembrane receptor protein that has been implicated in the regulation of the Wnt signaling pathway (cofetuzumab pelidotin) [94–102].
- In the cytoplasm: dikkopf-1 (DKK1) modulators (DKN-01) [66–71]. Functioning as an extracellular antagonist, DKK1 binds to LRP5/6 co-receptors, interrupting their engagement with Wnt ligands and obstructing the activation of the canonical Wnt pathway. This impediment leads to a halt in the accumulation and nuclear movement of β-catenin [140].
- Within the nucleus e.g. inhibiting the target canonical pathway genes [125, 126] or CREB-binding protein (CBP) / β-catenin inhibitors (ICG-001, PRI-724, PRI-724 [26, 56–60, 89–96). CBP serves as a coactivator for transcription within the canonical Wnt pathway, collaborating with transcription factors such as β-catenin. It amplifies the transcription of Wnt target genes by modifying chromatin structure through the acetylation of histones [141].
- Within other signaling pathways that interact with Wnt including SHH (vismodegib, sonidegib, itraconazole, glasdegib, patidegib, LY2940680, ENV-101) as the most visible example [101–121].

While compounds acting on β-catenin degradation complex show activity in preclinical studies, their clinical activity

has not been confirmed yet (NVP-TNKS656, XAV939) [54, 55]. Numerous limitations accompany the development of Wnt pathway inhibitors. They include: the non-obvious role of Wnt elements in cancer development and progression, its role in physiological processes, its complexity. Notably, WNT inhibitors have the potential to serve not only in cancer therapy but also in a supportive capacity to mitigate treatment--related toxicity [11–17, 142].

Numerous novel molecules have undergone scrutiny in either preclinical investigations or clinical trials. A portion of these compounds has progressed to phase 2 clinical trials, marking the mid--point in the translational process depicted in figure 1.

Conclusions

The precise equilibrium and meticulous regulation observed in the Wnt pathway underline its paramount importance in maintaining cellular homeostasis, thereby delineating it as a promising focal point for therapeutic interventions directed at malignancies. The Wnt pathway branches into canonical and noncanonical categories, each instigating distinctive signaling cascades through specific receptor engagement. A comprehensive understanding of these pathways and their constituent elements is imperative for discerning their potential therapeutic ramifications. Presently, preclinical and clinical inquiries into Wnt elements are progressing, presenting an enticing trajectory for the development of novel anticancer therapies. However, the intricate nature of Wnt signaling, its dual role in both disease and physiological homeostasis, and the complexities surrounding its inhibitors do pose formidable challenges. The number of trials and the variety of molecular targets related to Wnt pathways, as well as different cancer indications within the patient population (tab. II) provide grounds for optimism regarding the possibility of advancing beyond the early phases of clinical trials in the journey from bench to bedside (fig. 1).

Article information and declarations

Author contributions

Renata Pacholczak-Madej – study conception and design, material collection, analysis and interpretation of results: all authors; manuscript preparation.

Mirosława Püsküllüoğlu – study conception and design, material collection, analysis and interpretation of results: all authors; manuscript preparation.

Paulina Frączek – manuscript critical review.

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