Systems-level biomarkers identification and drug repositioning in colorectal cancer

Hande Beklen, Esra Yildirim, Medi Kori, Beste Turanli, Kazim Yalcin Arga

Abstract

Colorectal cancer (CRC) is the most commonly diagnosed fatal cancer in both women and men worldwide. CRC ranked second in mortality and third in incidence in 2020. It is difficult to diagnose CRC at an early stage as there are no clinical symptoms. Despite advances in molecular biology, only a limited number of biomarkers have been translated into routine clinical practice to predict risk, prognosis and response to treatment. In the last decades, systems biology approaches at the omics level have gained importance. Over the years, several biomarkers for CRC have been discovered in terms of disease diagnosis and prognosis. On the other hand, a few drugs are being developed and used in clinics for the treatment of CRC. However, the development of new drugs is very costly and time-consuming as the research and development takes about 10 years and more than $1 billion. Therefore, drug repositioning (DR) could save time and money by establishing new indications for existing drugs. In this review, we aim to provide an overview of biomarkers for the diagnosis and prognosis of CRC from the systems biology perspective and insights into DR approaches for the prevention or treatment of CRC.

Key Words: Colorectal cancer; Colon cancer; Systems biology; Biomarker; Drug repositioning; Omics
Colorectal cancer (CRC) is the most frequently diagnosed cancer type in both women and men worldwide. It occurs in the colon or rectum and affects the large intestine or large bowel. Overall, CRC ranked second in mortality and third in incidence in 2020; and the estimated number of new cases was over 1.9 million with 935000 deaths in 2020[1]. The number is expected to increase to 2.2 million new cases and 1.1 million deaths by 2030[2].

In the absence of clinical symptoms, it is difficult to diagnose CRC in the early stages. According to the American Cancer Society, only 4 of 10 CRC patients are detected in the early stages. If detected in the early stages, the 5-year survival rate can be as high as 90%. The survival rate of CRC patients varies depending on the stages of cancer and metastasis. When metastasis occurs, the 5-year survival rate drops to 14%. Currently, surgical removal is the only curative choice for the treatment of early and localized CRC. In addition, a standard adjuvant strategy for patients with CRC stage III is chemotherapy[3]. As reported by Moertel et al[4], the combination of 5-fluorouracil (5-FU) with leucovorin reduced mortality by 33%.[4]. In addition, the multicenter international study (MOSAIC), which assessed the adjuvant treatment of CRC with oxaliplatin combined with 5-FU/leucovorin, showed an improvement in patients with stage III CRC[5].

The current various diagnostic strategies for CRC include invasive and non-invasive methods. Invasive methods consist of endoscopy and imaging tests. Endoscopy, which includes sigmoidoscopy and colonoscopy, is the most commonly used method for detecting CRC. Imaging tests such as nuclear magnetic resonance (NMR) and computed tomography (CT) are applied to diagnose severe focal lesions[6]. In addition, positron emission (PET)/CT, particularly fluorine-18-fluorodeoxyglucose PET/CT, is frequently used to diagnose CRC and evaluate patient response to treatment after radiochemotherapy for advanced rectal cancer[7]. As a non-invasive method, a fecal occult blood test is another diagnostic screening for CRC, identifying hemoglobin caused by gastrointestinal bleeding[8].

On the other hand, there is an urgent need for alternative, inexpensive and easy-to-measure methods for screening and therapy. An improvement in technologies in molecular biology provides an opportunity such as prognostic and predictive biomarkers to improve treatment selection or outcome for CRC. Following the completion of the Human Genome Project in 2003, studies of functional genomics (i.e. genomics, transcriptomics, proteomics, and metabolomics) have recently increased. Therefore, studies in the field of computational analysis, bioinformatics, and systems biology have gained importance to process data derived from functional genomics and apply a systematic perspective. Consequently, candidate biomarkers made further progress in understanding the mechanism of CRC[9].

The development of new drugs is very costly and time-consuming, as the research and development takes about 10 years and more than $1 billion[9,10]. Therefore, an approach called ‘drug repositioning’ (DR) could save time and costs by establishing new indications for existing drugs. DR has an effective strategy to provide already clinically tested drugs for complex diseases such as cancer[9].
SYSTEMS BIOLOGY APPROACHES TO DEFINE NEW BIOMARKERS AND DRUG REUSE

Systems biology is an approach that looks at biological systems as a whole and analyzes their interactions and how the interactions affect the behavior and function of the systems[11]. From a holistic view, it allows investigation from the level of cells, tissues, organs, and finally the whole organism. It also combines large amounts of data and reduces it to the levels of genomics, proteomics, and metabolomics to understand the mechanism of complex diseases and build a network model to develop new treatments[12].

Recently, the rising microarray and next-generation sequencing (NGS) technologies lead the accumulation of omics data to identify disease-associated genes, pathways, and biological networks. Therefore, systems biology methods are used to discover biomarkers and novel targets, as well as to develop novel therapeutics and treatment strategies. Genomics studies can enable early diagnosis, post-surgery surveillance, prediction of prognosis, and treatment response through the discovery of single nucleotide polymorphisms, somatic structural variations, copy number alterations, and chromosomal rearrangements in the genome[13]. Transcriptomics studies, involve the analysis of total RNA content, consisting of non-coding RNAs (ncRNAs), microRNAs (miRNA), long ncRNA (lncRNA), circular RNAs, piwi-interacting RNAs, and small nuclear RNAs. Unlike transcriptomics, proteomics provides information on protein function, protein-protein interactions, post-translational modifications, and is therefore important for discovering protein biomarkers in disease. However, proteins rather than DNA or RNA are usually selected as drug targets. The metabolomics approach works on metabolites that are essential for the growth, maintenance, and normal function of cells, such as amino acids, fatty acids, organic acids, sugars, etc.[14].

In short, systems biology strategies can unravel the mechanism underlying disease, provide therapeutic alternatives, and biomarkers that have diagnostic, prognostic, or theranostic properties by implementing different omics levels. While difficulties in cancer diagnosis and treatment regularly increase due to confounding pathogenesis and cellular heterogeneity, comprehensive analysis through the systems biology approach consistently helps to gain a comprehensive understanding of disease mechanisms and a greater vision in terms of diagnostic and prognostic biomarkers and targeted drug discovery[15,16]. The integration of high-throughput omics data from different biological levels has been the cornerstone of the systems biology approach of CRC. Moreover, predictions for drug development can be facilitated by the use of systems biology. The identification of biological targets and new promising drugs can be achieved by using in silico methods for DR by collecting clinical data at different omics levels and analyzing them within systematic and integrative pipelines[9].

In this review, we aim to provide an overview of systems-level biomarkers such as diagnostics and prognostics (Figure 1) and provide a deep understanding of the DR strategies for the treatment of CRC.

SYSTEMS-LEVEL BIOMARKERS

Despite considerable progress in CRC research aimed at elucidating the molecular mechanisms underlying disease carcinogenesis, the number of biomarkers that are applied in the clinic as routine practice to estimate risk, prognosis, and response to treatment is limited[15]. The lack of reliable and robust biomarkers to screen, monitor, and prevent CRC is a consequence of the heterogeneous nature of this disease and its complex multifactorial pathology[17].

Recent developments in proteomics, transcriptomics, metabolomics, and genomics have increased the number of potential biomarkers, which may ultimately advance the clinical management of CRC to reduce mortality and have led to a better understanding of not only disease progression but also the establishment of molecular biomarkers[8].

Diagnostic markers

A diagnostic biomarker is a measurable indicator that predicts or suggests the presence of a disease or related condition or determines a person with a subtype of the disease[18]. Screening strategies for CRC allow the detection and removal of adenomatous polyps and other premalignant lesions, resulting in a significant reduction in CRC mortality[19]. For these screening strategies in CRC, the identification of early, non-invasive, specific, and robust biomarkers remains an important
prerequisite.

Aberrant DNA methylation is a potential biomarker for the early detection of CRC. In one study, CpG methylation microarray analysis was performed in conjunction with a methylated DNA isolation assay to identify novel methylated genes at an early stage of CRC. Clinical validation tests showed that SDC2 had high sensitivity and specificity for detecting CRC, highlighting its diagnostic value as a blood-based biomarker for patients with CRC[20]. Li et al[21] identified a number of novel hypermethylated genes in CRC using the methylated-CpG island recovery assay in combination with microarrays. Of 211 hypermethylated candidate genes, only 3 novel hypermethylated genes, PHOX1B, GAD2, and FGF12, were selected for validation testing. These genes were better than VIM and SEPT9 in discriminating CRC tissues compared to control tissues, indicating that they have the potential to be used as biomarkers for early diagnosis of CRC. Another comprehensive genomic study[22] performed a genome-wide search for hypermethylation events in primary CRC
Beklen H et al. Systems level CRC biomarkers and DR

compared to normal colonic tissue using microarrays. As a result of the systematic methylome-wide analysis, ten newly identified methylation events distinguished neoplastic and non-neoplastic colonic mucosa from CRC patients. Among the ten methylated events, VSX2 had the highest diagnostic accuracy.

Abnormal changes in the transcriptome occur as a result of epigenetic changes and loss of genomic stability in CRC[23,24]. An increasing number of studies have demonstrated that ncRNAs, the best-studied form of the RNA pool, are hallmarks of CRC, and their association with invasion and metastasis of CRC cells offers ncRNAs as promising new biomarkers for the early diagnosis and treatment of CRC[25]. Among ncRNAs, miRNAs are known to have a profound relationship with the stages and progression of CRC[26]. A comprehensive transcriptomic study was conducted by Yamada and colleagues using the RNA-seq approach to discover a novel IncRNA biomarker in CRC. They reported significant upregulation of four IncRNAs, CRCAL-4, CRCAL-3, CRCAL-2, and CRCAL-1, in patients with CRC[27]. Using the Gene Ontology and Kyoto Encyclopedia of Genes and Genomes annotations, the expression of IncRNA NONHSAT074176.2 was found downregulated in CRC tissues, suggesting that it may be a potential diagnostic biomarker for CRC[28].

In addition to miRNA and IncRNA, circRNA is a new class of ncRNA that has emerged as a potential biomarker for various cancers including colorectal carcinogenesis. Li et al[29] identified several circRNAs that are significantly dysregulated in CRC tissue samples compared to adjacent normal mucosal tissues. Of the circRNAs analyzed, CircDDX17 showed strong potential as a diagnostic biomarker and therapeutic target for CRC.

Various proteomic approaches, mostly quantitative mass spectrometry (MS)-based technologies, have been used in the search for diagnostic biomarker candidates. To analyze the expression of proteins isolated from fresh-frozen human CRC tissue and the adjacent non-tumor tissue (12 patients), Ghazanfar et al[30] performed 2D PAGE coupled with MS. The results revealed a novel protein upregulated in CRC tissues, named ACTBL2. Hao and coworkers[31] examined 22 pairs of cancer tissues and adjacent healthy tissue samples collected from 22 participants using integrative proteomic analysis performed by high-resolution Fourier transform MS and revealed that DPEP1 was overexpressed in CRC tissues. Quesada-Calvo et al[32] examined 76 formalin-fixed paraffin-embedded (FFPE) colorectal tissue samples harvested from early CRC stages, including normal or inflamed mucosa, using label-free proteomics. Three biomarkers (KNG1, OLFM4, Sec24C) showed differences in expression levels in the early stages compared to normal and premalignant tissues. These results were verified by immunohistochemistry (IHC), although the experiment was conducted using liquid chromatography-tandem MS (LC-MS/MS). In another study, validation studies performed by Yamamoto et al[33] using FFPE CRC tissues showed that cyclophilin A, annexin A2, and aldolase A had high expression in cancerous tissues compared to non-cancerous tissues. A recent study identified seven potential biomarkers of CRC using differential expression analysis, systems biology, and proteomic analysis. These essential biomarkers, CALD1, CTNNB1, CXCL14, PTCH1, CXCL8, TNFAIP3, and NNMT, are associated with other important target proteins such as APC, MAPK, and GLI[34].

Circulating biomarkers have great potential for early detection and clinical management of CRC, as they are cost-effective, easily accessible, minimally invasive, and low-risk[35]. In a prospective cross-sectional pilot study, Ivancic et al[36] demonstrated that a panel of five blood proteins (leucine-rich alpha-2-glycoprotein 1, Epidermal growth factor receptor, inter-alpha-trypsin inhibitor heavy chain family member 4, hemopexin, and superoxide dismutase 3) performed well for the detection of CRC using targeted LC-MS/MS. Validation tests showed that the panel has a specificity of 70% with a sensitivity of over 89% (Area under the curve = 0.86). Bhardwaj et al[37] performed LC/multiple reaction monitoring MS followed by proximity extension assay to identify a plasma protein panel. They showed a promising five-protein signature consisting of mannan-binding lectin serine protease 1, osteopontin (OPN/SPP1), serum paraoxonase lactonase 3, transferrin receptor protein 1, and amphiregulin for early detection of CRC.

In another study, Yu et al[38] analyzed 127 CRC serum samples and 90 healthy control samples and identified protein serine/threonine kinase 4 as a potential diagnostic biomarker for CRC using MS/MS. Fan et al[39] conducted a proteomic study to identify serum proteins by a combination of high-performance liquid chromatography and MS. They showed that macrophage mannosyl receptor 1 and S100 calcium-binding protein (S100A9) could be robust candidate biomarkers for adenomatous polyps and colorectal carcinomas. A quantitative proteomic study also detected a panel of protein biomarkers of adenomatous polyps and colorectal...
carcinomas belonging to the serpin family, SERPINA1, SERPINA3, and SERPINC1, by multiplex quantification with an isobaric tag for relative and absolute quantification [40]. A study using label-free quantitative MS and protein microarray demonstrated adipophilin as a plasma biomarker to detect early-stage CRC [41].

Metabolomics studies focusing on disease-related metabolites allow clear differentiation of CRC patients from healthy controls, which is promising for the estimation of non-invasive biomarkers in the early diagnosis of CRC [42]. Fecal metabolic profiling studies provide important information to understand the details of CRC. To identify oncofetal diagnostic biomarkers, Ma et al [43] analyzed serum samples from CRC patients and healthy controls using an integrated proteomics and metabolomics approach. They detected ten candidate biomarkers consisting of 3-hydroxybutyric acid, L-valine, L-threonine, 1-deoxyxylulose, glycyne, MACF1, APOH, A2M, IGL®, and VDB. In another metabolomics study on fecal samples, Lin et al [44] indicated that fecal metabolic profiles can differentiate between CRC patients and healthy controls, highlighting the potential utility of NMR-based fecal profiling for early detection in patients with CRC.

Serum NMR-based metabolic profiling ensures a substantial signature of CRC and has potential as a detection and diagnostic tool for patients with CRC. They showed that the rates of acetate/glycerol and lactate/citrate can be discriminatory biomarkers for colorectal polyps and CRC, respectively [45]. Another serum metabolome study was performed by Nishiumi et al [46] using gas chromatography (GC)/MS and they created a predictive model for early detection of CRC. Taurine, alanine, and 3-aminoisobutyrate showed discrimination between CRC patients in a recent study [47]. For urinary metabolic studies, urine samples may provide utility for the diagnosis of early and advanced stages of CRC. In an H-NMR-based metabolomic study, urine metabolites from CRC patients and healthy controls were profiled, including elevated acetoacetate, guanidinoacetate, cis-aconitate, trans-aconitate, glutamine, and homocysteine levels, as well as reduced creatinine, phosphorylcholine, dimethylsulfone, asparagine, alanine, isocitrate, hippurate, methyamine, cysteine, and phenylalanine levels [48]. A total of 16 promising urinary metabolites were detected to distinguish stage I/II CRC patients from healthy controls. In another NMR-based study, urine metabolomics profiles clearly and accurately distinguished CRC patients from healthy controls [47]. The results of the study showed that among the metabolites analyzed, only 6 metabolites significantly increased or decreased compared to healthy patients. Using capillary electrophoresis time-of-flight MS (CE-TOF/MS), Uchiyama et al [49] identified the interaction of CRC stages with the up- and down-regulation of various serum metabolites. They showed that benzoic acid might be a promising diagnostic biomarker for CRC patients. In a recent study, Liu et al [50] pointed out that miRNA and metabolite signatures have high diagnostic efficiency for CRC patients using two new methods, namely metabolomics based on GC/MS and serum miRNA detection. A study combining untargeted and targeted metabolomics showed that the differentiation of CRC patients from healthy controls revealed significant differences in serum concentrations of one endocannabinoid, two glycerophospholipids, and two sphingolipids [51].

In recent years, the number of metagenomic studies has gained significance, offering the opportunity to identify new diagnostic biomarkers for CRC clinical management. In Saudi Arabia, a comparative metagenomics study was conducted at a single center to understand the role of mucosal intestinal microbiota in CRC patients [52]. As a result of this study, among 11 genera found specific to CRC patients, Bacteroides fragilis and Fusobacterium were discovered to be present in the patient group compared to the control group. To identify the microbial composition of the microbiota in CRC, Kostic et al [53] performed whole-genome sequencing of nine CRC patients and healthy controls. This study revealed species-specific changes in the CRC microbiota, leading to diagnostic and clinical strategies for these patients. Using metagenomic data, Zeller et al [54] demonstrated that functional and taxonomic relationships with CRC and the ability to detect CRC determine early-stage disease from the fecal microbiota. While the metagenomics approach resolves associations between the gut microbiota and colorectal carcinogenesis, it holds promise for biomarker discovery for disease diagnosis and treatment. The biomarkers discovered in CRC are shown in Table 1.

The systems biology approach is a promising technology for the detection of novel diagnostic biomarkers in CRC. Despite the ever-increasing biomarker research based on systems biology, there is still a need to identify new biomarkers that have a crucial role in the early diagnosis and treatment of CRC, which are simple, inexpensive, and non-invasive, but have high sensitivity and specificity.

[40] A study using label-free quantitative MS and protein microarray demonstrated adipophilin as a plasma biomarker to detect early-stage CRC [41].

Metabolomics studies focusing on disease-related metabolites allow clear differentiation of CRC patients from healthy controls, which is promising for the estimation of non-invasive biomarkers in the early diagnosis of CRC [42]. Fecal metabolic profiling studies provide important information to understand the details of CRC. To identify oncofetal diagnostic biomarkers, Ma et al [43] analyzed serum samples from CRC patients and healthy controls using an integrated proteomics and metabolomics approach. They detected ten candidate biomarkers consisting of 3-hydroxybutyric acid, L-valine, L-threonine, 1-deoxyxylulose, glycyne, MACF1, APOH, A2M, IGL®, and VDB. In another metabolomics study on fecal samples, Lin et al [44] indicated that fecal metabolic profiles can differentiate between CRC patients and healthy controls, highlighting the potential utility of NMR-based fecal profiling for early detection in patients with CRC.

Serum NMR-based metabolic profiling ensures a substantial signature of CRC and has potential as a detection and diagnostic tool for patients with CRC. They showed that the rates of acetate/glycerol and lactate/citrate can be discriminatory biomarkers for colorectal polyps and CRC, respectively [45]. Another serum metabolome study was performed by Nishiumi et al [46] using gas chromatography (GC)/MS and they created a predictive model for early detection of CRC. Taurine, alanine, and 3-aminoisobutyrate showed discrimination between CRC patients in a recent study [47]. For urinary metabolic studies, urine samples may provide utility for the diagnosis of early and advanced stages of CRC. In an H-NMR-based metabolomic study, urine metabolites from CRC patients and healthy controls were profiled, including elevated acetoacetate, guanidinoacetate, cis-aconitate, trans-aconitate, glutamine, and homocysteine levels, as well as reduced creatinine, phosphorylcholine, dimethylsulfone, asparagine, alanine, isocitrate, hippurate, methyamine, cysteine, and phenylalanine levels [48]. A total of 16 promising urinary metabolites were detected to distinguish stage I/II CRC patients from healthy controls. In another NMR-based study, urine metabolomics profiles clearly and accurately distinguished CRC patients from healthy controls [47]. The results of the study showed that among the metabolites analyzed, only 6 metabolites significantly increased or decreased compared to healthy patients. Using capillary electrophoresis time-of-flight MS (CE-TOF/MS), Uchiyama et al [49] identified the interaction of CRC stages with the up- and down-regulation of various serum metabolites. They showed that benzoic acid might be a promising diagnostic biomarker for CRC patients. In a recent study, Liu et al [50] pointed out that miRNA and metabolite signatures have high diagnostic efficiency for CRC patients using two new methods, namely metabolomics based on GC/MS and serum miRNA detection. A study combining untargeted and targeted metabolomics showed that the differentiation of CRC patients from healthy controls revealed significant differences in serum concentrations of one endocannabinoid, two glycerophospholipids, and two sphingolipids [51].

In recent years, the number of metagenomic studies has gained significance, offering the opportunity to identify new diagnostic biomarkers for CRC clinical management. In Saudi Arabia, a comparative metagenomics study was conducted at a single center to understand the role of mucosal intestinal microbiota in CRC patients [52]. As a result of this study, among 11 genera found specific to CRC patients, Bacteroides fragilis and Fusobacterium were discovered to be present in the patient group compared to the control group. To identify the microbial composition of the microbiota in CRC, Kostic et al [53] performed whole-genome sequencing of nine CRC patients and healthy controls. This study revealed species-specific changes in the CRC microbiota, leading to diagnostic and clinical strategies for these patients. Using metagenomic data, Zeller et al [54] demonstrated that functional and taxonomic relationships with CRC and the ability to detect CRC determine early-stage disease from the fecal microbiota. While the metagenomics approach resolves associations between the gut microbiota and colorectal carcinogenesis, it holds promise for biomarker discovery for disease diagnosis and treatment. The biomarkers discovered in CRC are shown in Table 1.

The systems biology approach is a promising technology for the detection of novel diagnostic biomarkers in CRC. Despite the ever-increasing biomarker research based on systems biology, there is still a need to identify new biomarkers that have a crucial role in the early diagnosis and treatment of CRC, which are simple, inexpensive, and non-invasive, but have high sensitivity and specificity.
| Diagnostic biomarker                  | Molecular level | Sample                  | Expression | Ref.                        |
|--------------------------------------|-----------------|-------------------------|------------|-----------------------------|
| Actin Beta-Like 2                    | Protein         | Fresh frozen tissue     | ↑          | Ghazanfar et al[30], 2017   |
| Dipeptidase 1                        | Protein         | Fresh frozen tissue     | ↑          | Hao et al[31], 2017         |
| Olfamectomedin-4                     | Protein         | FFPE tissue             | ↑          | Quesada-Calvo et al[32], 2017|
| Kininogen-1                          | Protein         | FFPE tissue             | ↑          | Yamamoto et al[33], 2016    |
| Transport Protein Sec-24             | Protein         | FFPE tissue             | ↑          | Ivancic et al[36], 2020     |
| Cyclophilin A                        | Protein         | Serum                   | ↑          | Ilyas et al[34], 2020       |
| Annexin A2                           | Protein         | Plasma                  | ↓          | Bhardwaj et al[37], 2019    |
| Aldolase A                           | Protein         | Serum                   | ↑          | Yu et al[38], 2017          |
| Leucine-Rich Alpha-2 Glycoprotein 1  | Protein         | Serum                   | ↑          | Fan et al[39], 2016         |
| Epidermal Growth Factor Receptor     | Protein         | Serum                   | ↑          | Ma et al[40], 2012          |
| Hemeopexin                           | Protein         | Serum                   | ↑          | Peltier et al[41], 2011     |
| Superoxide Dismutase 3               | Protein         | Serum                   | ↑          | Ma et al[42], 2012          |
| Inter-Alpha-Trypsin Inhibitor Heavy-Chain Family Member 4 | Protein         | Serum                   | ↑          | Ma et al[43], 2012          |
| Mannan Binding Lectin Serine Protease 1 | Protein         | Serum                   | ↑          | Ma et al[44], 2012          |
| Osteopontin                          | Protein         | Serum                   | ↑          | Ma et al[45], 2012          |
| Serum Paraoxonase Lactonase 3        | Protein         | Serum                   | ↑          | Ma et al[46], 2012          |
| Transferrin Receptor Protein 1       | Protein         | Serum                   | ↑          | Ma et al[47], 2012          |
| Amphiregulin                         | Protein         | Plasma                  | ↓          | Ma et al[48], 2012          |
| Adipophilin                          | Protein         | Plasma                  | -          | Ma et al[49], 2012          |
| Caldesmon 1                          | Protein         | Fresh Frozen Tissue     | -          | Ma et al[50], 2012          |
| Catenin Beta 1                       | Protein         | Plasma                  | ↑          | Ma et al[51], 2012          |
| C-X-C Motif Chemokine Ligand 14      | Protein         | Plasma                  | ↑          | Ma et al[52], 2012          |
| Protein patched homolog 1            | Protein         | Plasma                  | ↑          | Ma et al[53], 2012          |
| Interleukin-8, Tumor necrosis factor-alpha induced protein 3, Nicotinamide N-methyltransferase | Protein         | Plasma                  | ↑          | Ma et al[54], 2012          |
| Mitogen-activated protein kinase      | Protein         | Plasma                  | ↑          | Ma et al[55], 2012          |
| Adenomatous polyposis coli           | Protein         | Plasma                  | ↑          | Ma et al[56], 2012          |
| Zinc finger protein                  | Protein         | Plasma                  | ↑          | Ma et al[57], 2012          |
| Serine/Threonine Kinase 4            | Protein         | Serum                   | ↑          | Ma et al[58], 2012          |
| Macrophage mannose receptor 1        | Protein         | Serum                   | ↑          | Ma et al[59], 2012          |
| Sl100 calcium binding protein        | Protein         | Serum                   | ↑          | Ma et al[60], 2012          |
| Alpha-1-antitrypsin                  | Protein         | Serum                   | ↑          | Ma et al[61], 2012          |
| Alpha-1-antichymotrypsin             | Protein         | Serum                   | ↑          | Ma et al[62], 2012          |
| Anti- Thrombin 3                     | Protein         | Serum                   | ↑          | Ma et al[63], 2012          |
| 3-Hydroxybutyric Acid                | Protein         | Serum                   | ↑          | Ma et al[64], 2012          |
| Microtubule Actin Crosslinking Factor 1 | Protein         | Serum                   | ↑          | Ma et al[65], 2012          |
| L-Valine                             | Protein         | Serum                   | ↑          | Ma et al[66], 2012          |
| L-Threonine                          | Protein         | Serum                   | ↑          | Ma et al[67], 2012          |
| L-Deoxyglucose                       | Protein         | Serum                   | ↑          | Ma et al[68], 2012          |
| Glycine                              | Protein         | Serum                   | ↑          | Ma et al[69], 2012          |
Apolipoprotein H  |  Protein  |  Serum  |  ↓  |  Ma et al[43], 2012
--- | --- | --- | --- | ---
Alpha-2-Macroglobulin  |  Amino acid  |  Urine  |  ↓/High  |  Wang et al[48], 2017
Immunoglobulin Lambda Locus  |  Amino acid  |  Urine  |  ↓/Low  |  Wang et al[48], 2017
Vitamin-D-binding protein  |  Amino acid  |  Urine  |  ↓/High  |  Wang et al[48], 2017
Acetoacetate, Guanidinoacetate  |  Amino acid  |  Urine  |  ↓/Low  |  Wang et al[48], 2017
Cis-aconitate, Trans-aconitate, Glutamine  |  Amino acid  |  Urine  |  ↓/High  |  Wang et al[48], 2017
Homocysteine  |  Amino acid  |  Urine  |  ↓/Low  |  Wang et al[48], 2017
Creatinine, Phosphorylcholine  |  Amino acid  |  Urine  |  ↓/Low  |  Wang et al[48], 2017
Dimethyl sulfone, Asparagine, Alanine  |  Amino acid  |  Urine  |  ↓/Low  |  Wang et al[48], 2017
Isocitrate, Hippurate, Methylamine  |  Amino acid  |  Urine  |  ↓/Low  |  Wang et al[48], 2017
Cysteine, Phenylalanine  |  Amino acid  |  Urine  |  ↓/Low  |  Wang et al[48], 2017
Isoleucine, β-Hydroxybutyrate, lactate, acetate, glutamate, choline, glycine, serine, glucose  |  Amino acid  |  Biopsy  |  High  |  Nishiumi et al[46], 2012
Taurine, alanine, β-Aminoisobutyrate, valine  |  Amino acid  |  Urine  |  High  |  Kim et al[47], 2019
Threonine, glycerol, hippurate, ascorbate, creatinine and citrate  |  Amino acid  |  Urine  |  Less  |  Kim et al[47], 2019
Proline, succinate, isoleucine, leucine valine, alanine, glutamate, dimethylglycine and lactate  |  Amino acid  |  Fecal  |  High  |  Lin et al[44], 2019
Short Chain Fatty Acids, (acetate, propionate and butyrate), glucose, glutamine  |  Amino acid  |  Fecal  |  Less  |  Lin et al[44], 2019
Sphinganine, endocannabinoids  |  Amino acid  |  Serum  |  High  |  Martin-Blázquez et al[51], 2019
CRCAL-4, CRCAL-3, CRCAL-2 (Long Intergenic Non-Protein Coding RNA 858), and CRCAL-1  |  IncRNA  |  CRC cell line  |  ↑  |  Yamada et al[27], 2018
NONHSAT074176.2  |  IncRNA  |  Fresh frozen tissue  |  ↓  |  Zhang et al[28], 2018
CircDDX17  |  IncRNA  |  Fresh frozen tissue  |  Dysregulated  |  Li et al[29], 2018
Syndecan 2  |  Gene  |  Fresh frozen tissue  |  ↑  |  Oh et al[20], 2013
PHOX1B, Glutamic acid de-carboxylase 2, and Fibroblast Growth Factor 12  |  Gene  |  Fresh frozen tissue  |  ↑  |  Li et al[21], 2012
Visual System Homeobox 2  |  Gene  |  Neoplastic colonic tissue  |  ↑  |  Mori et al[22], 2011

CRC: Colorectal cancer.

**Prognostic markers**

A prognostic biomarker is a biological characteristic that provides details on the patient’s disease progression[55]. Prognostic biomarkers can be used to detect the progression of a pathological condition, including early recurrence and mortality[56, 57]. Recent studies have shown that the APC mutation is the most frequently seen mutation in CRC which has prognostic biomarker potential for clinical outcome[58]. Appropriate validation of this biomarker is needed to advance detection and better prognosis toward clinical outcome[59]. In a cohort genomic study, mutant TP53 status was associated with adjuvant 5-FU therapy in stage III CRC patients[60]. However, other research showed that mutant TP53 was significantly correlated with poor survival[61].

Micu et al[62] performed a retrospective study of 103 patients who had curative surgery for CRC, and they showed that the 5-year survival rate of patients with microsatellite instability (MSI) tumors was higher than that of the microsatellite stable tumor group. Another study showed that patients who had high MSI had longer disease-free survival (DFS) than patients with low MSI. This study shows that MSI has the potential to be a prognostic clinical parameter[63].

Mizuno et al[64] investigated the impact of SMAD4 gene mutation on clinical features and outcomes in patients undergoing liver resection for colorectal liver metastases using a next-generation somatic gene sequencing platform. In the
validation series, which included 237 patients, mutations in the SMAD4 gene were correlated with a worse 3-year overall survival (OS) rate and were an autonomous predictor of worse OS. In a prospective study, multiple pan-cancer profiles of 33 Chinese mCRC patients were characterized utilizing extensive NGS. Further results showed that SMAD4 and NFI mutations may be promising biomarker candidates for poor prognosis[65].

The impact of BRAF and KRAS on survival in stage II and III MSI colon cancer patients was investigated. BRAF and KRAS vs double wild-type mutations remained prognostic in stage II and III MSI colon cancer patients after multivariate analysis. These mutations should be analyzed if these genes are considered prognostic markers [66]. A survival study in patients with curatively resected stage I-III CRC demonstrated that the existence of KRAF and BRAF mutations was correlated with poor OS and DFS. In Japanese patients with successfully dissected CRC, KRAS and BRAF were associated with poorer survival, independent of MSI[67].

Nguyen et al[68] showed that the prognostic marker of 113 probe sets (CRC-113) was associated with disease incidence and survival in patients with CRC. Moreover, the CRC patients selected by the CRC-113 were able to benefit from postoperative chemotherapy, indicating that the CRC-113 gene signature could be a potential prognostic biomarker for CRC prediction.

High-throughput transcriptome studies provide significant opportunities to identify biomarkers that are effective for CRC prognosis. Zheng et al[69] indicated that MALAT1 LncRNA expression is upregulated in CRC tissues, as revealed by real-time reverse transcriptase-polymerase chain reaction (RT-qPCR) analysis of 146 fresh tumor tissue samples. Therefore, a higher expression level of MALAT1 might be involved in CRC progression and therefore serve as a prognostic biomarker for patients with stage II/III CRC.

In another transcriptomic study, Ohtsuka et al[70] examined a large panel of lncRNA expression levels from CRC datasets of The Cancer Genome Atlas (TCGA) and recognized that H19 is the lncRNA most associated with OS of CRC patients. High expression levels of H19 have been related to tumor differentiation and advanced Tumor-Node-Metastasis stage[71] and may be a prognostic biomarker candidate for OS and DFS. A comprehensive study was conducted to reveal the role of 21 cancer-related lncRNAs in the prognosis of CRC using the PCR array. Their results showed that AFAP1-A5, BCA4, H19, HOXA-AS2, MALAT1, or PVT1 were upregulated, while ADAMTS9-AS2 was downregulated, and therefore seven lncRNAs have significant potential as a prognostic factor for CRC patients[72].

With regard to the discovery of novel miRNAs as biomarkers, recent studies suggested that miR-429 may be a novel independent biomarker for CRC prognosis[73, 74]. Sun and coworkers indicated that downregulation of miR-429 was significantly associated with poor prognosis for stage II/III colorectal carcinomas using RT-qPCR and tissue microarrays[74]. Another study focusing on miR-249 showed that overexpression of miR-249 correlated with a worse prognosis of CRC[73]. In a comprehensive study, Kandimalla et al[75] identified an 8-miRNA signature with high statistical significance consisting of hasa-mir-191, hasa-mir-200b, hasa-mir-30b, hasa-mir-30c2, hasa-mir-33a, hasa-mir-362, hasa-mir-429, and hasa-mir-744, representing a significantly improved prognostic potential for CRC patients. Levf et al[76] recognized a novel CRC-specific transcript, VNN1-AB, from whole-transcriptome sequencing of seven CRC cell lines. This transcript had high sensitivity and complete specificity for CRC and therefore might be a potential prognostic factor for CRC.

The most widely used reliable prognostic protein biomarker in clinical practice is carcinoembryonic antigen (CEA), a high molecular weight glycoprotein secreted by 90% of CRCs. Although elevated CEA levels are associated with tumor progression, this is not specific to CRC, as they can also be caused by other conditions such as inflammatory bowel disease, liver disease, pancreatitis, and other malignancies[77-79]. In a recent study, Kirana et al[80] used a combination of laser microdissection (LM), 2D-DIGE, and MALDI-TOF MS methods to identify proteins that participate in the spread of CRC. First, cancer cells from patients with primary colorectal tumors at stage II were extracted into two groups using LM. Analysis of the isolated cancer cells showed an association of the expression of HLAB, 14-3-3b protein, ADAMTS2, LTB3, NME2, and JAG2 with tumor progression, invasion, and metastasis.

The collagen proteins are promising biomarker candidates, as the present study demonstrated that certain collagen proteins are upregulated in metastatic CRC. Comparative analysis of colorectal liver metastatic tissue with non-cancerous adjacent liver tissue using the MS-based proteomics approach has shown upregulation of 19 of 22 collagen chains. Further verification by IHC revealed that collagen type XII is significantly upregulated in CRC tissue[81].
In another study, Mori et al.[82] used isobaric tags defined in the Isobaric Tags for Relative and Absolute Quantification (iTRAQ) methodology for proteomic analysis to determine novel biomarkers in lymph node metastases (LNM) in patients with CRC. The analysis revealed that 60 differentially expressed proteins were significantly related to LNM in CRC patients. Among these 60 proteins, the HSP47 protein was selected for detailed study as it has a general function and specific roles in the malignant phenotype. Validation analysis by IHC proved that HSP47 protein was highly expressed in CRC in contrast to adjacent healthy colonic mucosa. Another comparative proteomics study[83] was performed by the same group using the iTRAQ method. According to univariate and multivariate logistic analyses, the high expression level of ezrin protein was prognostic in CRC patients. Moreover, some studies have indicated that the higher expression level of Ezrin protein is associated with the aggressive behavior of tumors and poor prognosis of CRC[84,85].

Regarding the identification of robust biomarkers for CRC recurrence, a recent study[86] identified eight proteins as significant key markers with prognostic significance for tumor recurrence: Collagen VI, Forkhead Box O3, Inositol Polyphosphate-4-Phosphatase, LcK Tyrosine Kinase, Phospho-PEA15 (Ser116), Phospho-PRA40, Rad51, and Phospho-S6 (Ser240-244). Snoeren et al.[87] also demonstrated that higher expression of maspin is a prognostic biomarker for early recurrence in stage III and IV CRC patients.

Zhu et al.[88] performed a case-control study based on magnet-based fractionation coupled with matrix-assisted laser desorption/ionization time-of-flight MS (MALDI-TOF MS) to investigate serum samples from CRC patients. Using Fourier transform ion cyclotron resonance MS detection, peptides identified from a panel of proteins were alpha-tetraprotein, complement C4-A, fibrinogen alpha, the eukaryotic peptide chain-releasing factor GTP-binding subunit ERF3B, and angiotensinogen.

From a metabolomics perspective, there is an increasing number of studies focused on the discovery of biomarkers for CRC prognosis. In a prospective cohort study, Liesenfeld et al.[89] analyzed the urinary metabolite profiling of CRC patients using GC-MS and 1H NMR and showed that CRC patients before surgery can be distinguished from those after surgery. The metabolites analyzed were identified as prognostic biomarker candidates for the clinical management of CRC. Jiménez et al.[90] also conducted a prospective study using high-resolution magic-angle spinning nuclear magnetic resonance spectroscopy (HR-MAS NMR) to analyze metabolomics profiles of CRC and adjacent macroscopically normal (or "off-tumor") mucosa harvested from the same resection specimen. In a large, four independent cohort study, Qiu et al.[91] applied gas chromatography time-of-flight MS (GC-TOFMS) to analyze metabolites from CRC patients. They determined a distinctive metabolic signature with 15 significant biomarkers from CRC tissue samples, which has great prognostic and therapeutic potential. Chan et al.[92] performed global metabolic profiling using HR-MAS NMR and GC/MS methodology to analyze metabolites of biopsied colorectal tumor samples and their matched normal mucoses. Their results demonstrated that unique metabolic signatures correlated with anatomic and clinicopathologic features of CRC, shedding light on providing novel phenotypic prognostic biomarkers for CRC management.

For the identification of reliable prognostic biomarkers, genomic studies provide an increasingly detailed and complex picture of the pathogenesis of CRC. The identification of novel prognostic biomarkers, their validation and translation into clinical application are very important in understanding the pathogenesis of CRC and to clarify issues such as distant metastasis and recurrence. Detailed information on prognostic biomarkers is provided in Table 2.

**DR**

DR from a systems biology perspective can be categorized as signature-based DR and network-based DR. Signature-based DR depends on gene expression signatures and compares between drug-gene and expression profiles of disease-gene[93,94]. Connectivity Map (CMap) is one of the most used tools which was established for signature-based approaches and it is a publicly available resource employed to detect small molecules and their mechanisms of action, chemicals or physiological processes, diseases, and drugs[95]. This approach is important for the discovery of new candidates and the experimental evaluation of computationally predicted candidates. Another category of DR is network-based DR, which is used to identify molecular mechanisms and key biomolecules in many diseases, including cancer, by creating
| Prognostic biomarker                                                                 | Molecular level | Sample                                | Expression | Ref.                                      |
|----------------------------------------------------------------------------------|-----------------|---------------------------------------|------------|-------------------------------------------|
| Carcinoembryonic antigen                                                          | Protein         | Plasma                                | ↑          | Li et al[79], 2018                        |
| Major histocompatibility complex, class I, B (HLAB)                               | Protein         | Fresh Frozen Tissue                   | ↑          | Kirana et al[80], 2019                    |
| 14-3-3b protein (YWHA B)                                                          |                 |                                       |            |                                          |
| A disintegrin and metalloproteinase with thrombospondin motifs 2                  |                 |                                       |            |                                          |
| Leukotriene B3                                                                     |                 |                                       |            |                                          |
| Nucleoside Diphosphate Kinase 2                                                   |                 |                                       |            |                                          |
| Jagged Canonical Notch Ligand 2                                                   |                 |                                       |            |                                          |
| Collagen type XII (FACIT)                                                         | Protein         | Colorectal liver metastasis tissue    | ↑          | van Huizen et al[81], 2019                |
| Heat shock protein 47                                                              | Protein         | Fresh Frozen Tissue                   | ↑          | Mori et al[82], 2017                     |
| Ezrin protein                                                                     | Protein         | Cells and tissue                      | ↑          | Patara et al[83], 2011                   |
| Collagen VI (COL6)                                                                 | Protein         | Fresh Frozen Tissue                   | ↑          | Clarke et al[86], 2017                   |
| Forkhead box C3                                                                   |                 |                                       |            |                                          |
| RAD51 (DNA repair protein RAD51 homolog 1)                                         |                 |                                       |            |                                          |
| Lymphocyte-specific protein tyrosine kinase                                       |                 |                                       |            |                                          |
| Inositol polyphosphate-4-phosphatase                                               |                 |                                       |            |                                          |
| Phospho-PEA15 (Ser116)                                                            |                 |                                       |            |                                          |
| Phospho-S6 (Ser240-244)                                                           |                 |                                       |            |                                          |
| Phospho-PRA540 (Thr-246)                                                          |                 |                                       |            |                                          |
| Mammary serine protease inhibitor                                                 | Protein         | Fresh Frozen Tissue                   | ↑          | Snoeren et al[87], 2013                  |
| Alpha-fetoprotein                                                                 | Protein         | Serum                                 | -          | Zhu et al[88], 2013                       |
| Complement C4-A (C4A)                                                             |                 |                                       |            |                                          |
| Fibrinogen alpha                                                                  |                 |                                       |            |                                          |
| Eukaryotic peptide chain release factor GTP-binding subunit ERF38 (CSPT2)         |                 |                                       |            |                                          |
| Angiotensinogen                                                                   |                 |                                       |            |                                          |
| Hippurate, Butyrate                                                                | Amino acid      | Urine                                 | ↑          | Liesenfeld et al[89], 2015               |
| Glycerol, Galactarate                                                             |                 |                                       |            |                                          |
| Urea, Carnitine                                                                   | Amino acid      | Urine                                 | ↓          | Liesenfeld et al[89], 2015               |
| AFAP1 Antisense RNA 1                                                              | IncRNA          | Datasets                              | ↑          | Li et al[72], 2016                       |
| Breast Cancer Anti-Estrogen Resistance 4                                           |                 |                                       |            |                                          |
| H19                                                                              |                 |                                       |            |                                          |
| HOXA Cluster Antisense RNA 2                                                       |                 |                                       |            |                                          |
| Metastasis Associated                                                             |                 |                                       |            |                                          |
| Lung Adenocarcinoma Transcript 1 (MALAT1)                                          |                 |                                       |            |                                          |
| Plasmacytoma Variant Translocation 1                                              | IncRNA          | Datasets                              | ↓          | Li et al[72], 2016                       |
| ADAMTS9 Antisense RNA 2                                                            | microRNA        | Fresh Frozen Tissue                   | ↓          | Li et al[73], 2013                       |
| miR-429                                                                          |                 |                                       |            |                                          |
| hsa-mir-191, hsa-mir-200b                                                          | microRNA        | Datasets                              | -          | Kandimalla et al[75], 2018               |
| hsa-mir-30b, hsa-mir-30c                                                          |                 |                                       |            |                                          |
disease-gene-drug triangles[94]. There are many examples of network-based pipelines and DR tools[96].

In this section, we have mentioned the drugs that have been repositioned using either network-based or signature-based DR strategies. However, we have categorized the drugs in relation to whether only computational prediction or in vit re assay has been carried out or clinical trials have been performed (Figure 2).

**Computational predictions**

Chung and collaborators presented a novel computational framework called Functional Module Connectivity Map for DR and used their framework for CRC. In their framework, the researchers first analyzed microarray data consisting of 32 CRC samples and 32 controls to find differentially expressed genes (DEGs). Then, gene-gene interaction networks were reconstructed around cancer and control samples, respectively. The gene-gene interaction networks were reduced to the function-function network using functional modules as nodes. Using the gene selection-by-trend-of-progression procedure, highly expressed hub genes in the function-function networks were identified and used as CMap query. CMap analysis culminated in several already known and effective CRC drugs. To validate the results of the CMap analysis, the researchers also performed cell viability assays to obtain eight candidates. As a result, the following drugs: GW-8510, ethacrynic acid, ginkgolide A, and 6-azathymin were identified as drugs that inhibit CRC[97]. As the researchers demonstrated the upregulation of RRM2 in CRC by bioinformatics analysis, they sought to find a novel RRM2 inhibitor that has the potential to be used in CRC. To this end, the researchers first evaluated the expression of 3 RR subunits (RRM1, RRM2, and RRM2B) in cancer and normal cells using the Oncomine database and showed that the expression of RRM2 is upregulated in CRC. To further evaluate the effects of RRM2 on CRC, the researchers also analyzed microarray data (GSE8671 and GSE1710) and determined that RRM2 is a potential therapeutic target for CRC. After obtaining this information, the researchers attempted to find novel RRM2 inhibitors via CMap. They analyzed a microarray dataset (GSE15212) that included RRM2-knockdown SW480 human CRC cells and uncovered DEGs that were used as CMap queries. Four drugs (phenoxybenzamine, doxorubicin, daunorubicin, and GW-8510) with the highest CMap score were experimentally analyzed by cell viability assay and western blot analysis. The experiments showed that of the 4 drugs, GW-8510 prevented RRM2 expression. Thus, the study demonstrated the potential of GW-8510 as a CRC therapeutic agent targeting the inhibition of RRM2[98].

Another DR study used machine learning and molecular docking in colon cancer. For this purpose, the RNAseq data of colon adenocarcinomas were obtained from TCGA resource and the data were analyzed to find the DEGs. The significance of the DEGs was then validated via a machine learning approach and a total of 34 gene signatures were obtained. For the application of molecular docking, 34 gene signatures were converted into 3D structures and the list of FDA-approved anticancer drugs was used for docking (81 drugs). As a result of the molecular docking analyses, 4 targets emerged, namely GLTP, PTPRN, VEGFA, and FABP6. The 4 targets were investigated by literature search and both VEGFA and FABP6 were found to be upregulated in cancer cases; thus, they were considered potential targets. Docking studies showed that VEGFA and FABP6 had marked interactions with venetoclax and abemaciclib. However, the FABP6 gene has greater specificity for abemaciclib when compared with others. Therefore, this study suggested that abemaciclib targeting FABP6 has the potential to be a therapeutic target and needs further experimental validation[99]. Consequently, our research group applied a DR strategy by targeting the coexpression network of the protein Multidrug Resistance 1 (MDR1) expressed by the ABCB1
protein that causes chemotherapy failure. To this end, we reconstructed four different coexpression networks around ABCB1 and exploited their prognostic and diagnostic capabilities in CRC. We performed DR using a reverse effect of coexpression signatures and estimated drug candidates by molecular docking in terms of determining the interaction potential between drug and MDR1. In addition, we carried out an in silico cross-validation study using transcriptome data for ABCB1-mediated co-expressed genes in drug-resistant HT29 cells. As a result of the study, we proposed drug candidates (i.e., AG957, Ro-28-1675, Brazilin, Importazole, and PD407824) for CRC, especially by pointing out the importance of drug resistance in CRC[100] (Table 3).

Clinical and experimentally validated repurposed drugs

Metformin: Metformin is one of the most commonly used drugs in the treatment of type 2 diabetes mellitus. Metformin lowers blood glucose concentration without inducing hypoglycemia. As metformin is a readily available and inexpensive drug, numerous studies have been conducted on other potential indications[101]. In recent years, numerous in vitro and in vivo DR studies have shown that metformin can be used in the treatment or prevention of CRC. In an in vivo study, the effects of metformin treatment on diabetic rats were investigated. For this purpose, researchers injected STZ to induce diabetes in rats and injected 1,2-dimethylhydrazine to induce CRC. Then, 150 mg/kg metformin treatment was applied to rats once a week for 12 wk. Following metformin treatment and analysis of the results, it was shown that the number of precancerous lesions and cancer cell proliferation were reduced in rats [102]. In an in vitro study, HT29 cells were treated with metformin in a dose (0, 10 mmol/L/25 mmol/L/50 mmol/L) and time (24/48 h) dependent manner. The maximum dose used (50 mmol/L) for 48 h caused a maximum decrease (45%) in HT29 cells according to the proliferation index. Similarly, 60% of apoptotic cells were identified in the 50 mmol/L treatment for 48 h. Moreover, autophagic vacuoles were significantly conspicuous in metformin-treated cells at higher doses, whereas untreated cells showed a weak vacuole. In conclusion, the researchers indicated that metformin causes both apoptosis and autophagy of cultured HT29 cells[103]. A retrospective study based on a cohort of 1804 patients with diabetes and stage IV CRC showed that patients using metformin for their diabetes had better OS (hazard ratio = 0.85; 95% confidence interval = 0.76-0.94; P = 0.002) when considering their cancer status[104].

Aspirin: Due to its safety profile and widespread clinical use, aspirin is one of the best choices for drug repurposing. In a prospective cohort study, aspirin was shown to support the prevention of CRC. A total of 962 CRC cases were followed for 20 years, and patients were divided into aspirin users (325-mg tablets per week) and nonusers. The multivariate relative risk ratios with their 95% confidence intervals were 0.67-0.88
### Table 3 Drug repurposing candidates for the prevention and/or treatment of colorectal cancer

| Drug(s) | Pharmacological class | Original indication | CRC effect | Ref. |
|---------|-----------------------|---------------------|------------|------|
| **Based on computational approaches** | | | | |
| GW-8510, ethacrynic acid, ginkgolide A and 6-azathymine | GW-8510: Inhibitor of cyclin-dependent kinase-2; ethacrynic acid: Diuretic; ginkgolide A: Platelet-activating factor antagonist; 6-azathymine: D-3-aminoisobutyrate-pyruvate aminotransferase inhibitor | GW-8510: Prevention of chemotherapy-induced alopecia; ethacrynic acid: Treatment of high blood pressure and swelling; ginkgolide A: Treatment of a wide variety of cognitive and vascular disorders 6-azathymine: Has antibacterial and antiviral activities | Inhibit CRC cells | Chung et al [97], 2014 |
| GW-8510 | Inhibitor of cyclin-dependent kinase-2 | Prevention of chemotherapy-induced alopecia | CRC therapeutic agent which targets RRM2 inhibition | Hsieh et al [98], 2016 |
| Abemaciclib | Anti-neoplastic | Treatment of advanced or metastatic breast cancers | CRC therapeutic agent which targets FAB1/6 | Lihares-Blanco et al [99], 2020 |
| AG 957, Ro-28-1675, Brazilin, Importazole, PD 407824 | AG 957: Inhibitor; Ro-28-1675: Activator; Brazilin: Anti-inflammatory agent; Importazole: Inhibitor; PD 407824: Indoles and derivatives | AG 957: Protein tyrosine kinase; Ro-28-1675: Glucokinase activator; Brazilin: NF-kappaB inhibitor and a hepatoprotective agent; Importazole: Transport receptor importin-β; PD 407824: Wee1/Chk1 inhibitor | CRC drug candidates | Beklen et al [100], 2020 |
| **Based on clinically or experimentally validated approaches** | | | | |
| Metformin | Antidiabetic agent | Treatment of type 2 diabetes mellitus | Reduces pre-cancerous lesions and cancerous cell proliferation | Jia et al [102], 2015 |
| Aspirin | Nonsteroidal anti-inflammatory | Relieves minor aches, pains, and fevers | Regular, long-term aspirin use reduces CRC risk | Chan et al [103], 2005 |
| | | | Reduces CRC cell proliferation | Reddy et al [104], 2006 |
| | | | Daily use for about 5 yr is efficient in prevention, with a latency time of about 10 yr | Flossmann et al [105], 2007 |
| | | | Restains CRC tumor metastasis | Jin et al [106], 2019 |
| Cimetidine | Gastrointestinal agent | Treatment of ulcers and gastroesophageal reflux disease | Short course of cimetidine treatment has an impact on patient survival | Kelly et al [107], 1999 |
| Diclofenac | Nonsteroidal anti-inflammatory | Relieves pain and inflammation | Inhibits the adhesion of CRC cells and represses spread of cancer cells | Kobayashi et al [108], 2000 |
| | | | Reduces frequency of metastasis and increases survival rate | Matsumoto et al [109], 2002 |
| Chloroquine | Antimalarial | Treatment of malaria | Prolongs the probability of recurrence | Ali et al [110], 2018 |
| | | | Promotes cell death | Arisan et al [111], 2018 |
| | | | Increases cell inhibition and decreases reproduction | Sasaki et al [112], 2010 |
Use at high doses (40–160 μM) encourages lysosomal membrane permeabilization and cell death.

**Sulindac**
- Nonsteroidal anti-inflammatory
- Reduces pain, swelling, and joint stiffness due to arthritis
- Decreases final tumor counts and prevents CRC especially when given in intermittent doses
- Decreases polyp count

**Mesalazine**
- Anti-inflammatory
- Treatment of mild to moderate ulcerative colitis
- Decreases CRC cell number and enhances apoptosis
- Causes CRC cell cycle arrest and cell death

**Disulfiram**
- Enzyme inhibitor
- Alcohol addictive disorder
- Promotes cell viability inhibition

**Erlotinib**
- Anti-neoplastic
- Treatment of non-small cell lung and pancreatic cancer
- Contributes to enhanced progression-free survival and overall survival of metastatic CRC patients

**Park et al.** [120], 2014

**Chandra et al.** [122], 2017

**Davis et al.** [123], 2020

**Reinacher-Schick et al.** [125], 2003

**Koelink et al.** [126], 2010

**Stenvang et al.** [128], 2018

**Shi et al.** [130], 2017

**Kobayashi et al.** [111] investigated the mechanism of cimetidine in CRC. According to the analyses, they showed that cimetidine could inhibit adhesion of the CRC cell line to endothelial cells. Similarly, cimetidine can suppress the spread of cancer cells in a mouse model by decreasing the cell surface expression of E-selectin (an adhesion molecule) on endothelial cells. The effect of cimetidine on survival was studied using a total of 64 CRC-operated patients. Two weeks after surgery, patients were treated with 800 mg of cimetidine along with 200 mg of 5-FU (34 patients), while the placebo group (30 patients) received only 5-FU for one year. After treatment, the 10-year cumulative survival rate was 84.6% in the cimetidine group and 49.8% in the control group. The researchers also indicated that cimetidine reduced the incidence of metastasis in CRC patients. Finally, by immunostaining tumor tissue, the researchers showed that CRC patients who had high sLx or sLa epitope expression on tumor cells had an increased survival rate [112]. Another recent study investigated whether the time to CRC relapse can be prolonged with cimetidine. The clinical outcomes of a total

**Cimetidine**: The histamine receptor 2 antagonist cimetidine has intense immunomodulatory effects on the innate and adaptive immune systems [109]. The anticancer effects of cimetidine have been highlighted in many cancers, including CRC. To investigate the effects of cimetidine on colon carcinomas, 125 patients who planned to undergo elective colon or rectal excision were treated with cimetidine for 5 d before surgery. Using IHC, Kaplan-Meier, and computer video image analysis, the patients who received 800 mg of cimetidine twice daily were compared with the placebo group. Based on the results obtained, the researchers concluded that a short course of cimetidine treatment before surgery may have an impact on patient survival [110]. Another study by Kobayashi et al. [111] investigated the mechanism of cimetidine in CRC. According to the analyses, they showed that cimetidine could inhibit adhesion of the CRC cell line to endothelial cells. Similarly, cimetidine can suppress the spread of cancer cells in a mouse model by decreasing the cell surface expression of E-selectin (an adhesion molecule) on endothelial cells. The effect of cimetidine on survival was studied using a total of 64 CRC-operated patients. Two weeks after surgery, patients were treated with 800 mg of cimetidine along with 200 mg of 5-FU (34 patients), while the placebo group (30 patients) received only 5-FU for one year. After treatment, the 10-year cumulative survival rate was 84.6% in the cimetidine group and 49.8% in the control group. The researchers also indicated that cimetidine reduced the incidence of metastasis in CRC patients. Finally, by immunostaining tumor tissue, the researchers showed that CRC patients who had high sLx or sLa epitope expression on tumor cells had an increased survival rate [112]. Another recent study investigated whether the time to CRC relapse can be prolonged with cimetidine. The clinical outcomes of a total...
of 38 patients (stage III) were followed according to whether they received cimetidine for more than 2 years. Clinical outcomes were compared between the groups using univariate analysis and Kaplan-Meier modeling. It was found that days to relapse were significantly longer in the chemotherapy/cimetidine group than in the chemotherapy alone group. In addition, they reported that there was a direct association between the duration of cimetidine use and total cumulative cimetidine dose and cancer survival[115].

Diclofenac: The nonsteroidal anti-inflammatory drug diclofenac inhibits the enzyme cyclooxygenase-2 and has analgesic and antipyretic effects in addition to its anti-inflammatory function[114]. With increasing interest in the use of diclofenac in oncology, evidence of the anticancer effect of diclofenac in various cancers, including CRC[115], is increasing day by day. One study investigated the effect of diclofenac on the growth of murine C-26 colon carcinoma cells and C-26 tumors in syngeneic mice. For this purpose, the researchers fed the mice (which were implanted with colon tumors) diclofenac at a dose of 250 mg/L for 12 d. As a result of diclofenac treatment, cell death occurred on C-26 cells in a dose-dependent manner. In addition, diclofenac contributed to the inhibition of tumor growth in mice. Overall, the study suggested that diclofenac was a potential therapeutic and protective agent for colon cancer[116]. To reveal the molecular and therapeutic targets of diclofenac in colon cancer cells, the researchers used diclofenac in two cell types, HCT 116 (wt p53) and SW480 (mutant p53R273H). The results of the analysis culminated in subcytotoxic concentrations of diclofenac (400 μM) causing an increase in cell death in HCT 116 cells compared to SW480 cells. Furthermore, diclofenac promotes cell death by altering the PI3K/Akt/MAPK signaling axis in HCT 116 colon cancer cells[117].

Chloroquine: The main use of chloroquine is in the treatment of malaria. However, DR studies showed that the use of chloroquine is also effective in cancer treatment strategies, especially in combination with preferred anti-cancer agents[118]. In another study, the human CRC cell line HT29 was treated with chloroquine and/or 5-FU to investigate whether chloroquine potentiates the effect of 5-FU in CRC. For this purpose, cells were treated with chloroquine at different doses of 0.1, 1, 10, 100, or 1000 μM) for 12 and 24 h, and treated with 5-FU at doses of 0.01, 0.1, 1, 10, 100, or 1000 μM for 24, 48, and 72 h. Cells were also first treated with chloroquine (80 μM) for 12 h and then 5-FU. The researchers found that chloroquine co-treatment caused an increase in cell inhibition and a decrease in reproduction of about 33% compared to the control group. Accordingly, the researchers concluded that combination therapy with chloroquine and 5-FU is an impressive and promising strategy for curing CRC[119]. The effects of different concentrations of chloroquine on CRC were investigated using the HCT15 cell line. For this purpose, the researchers treated the cell lines with chloroquine at different doses (5 μM to 80 μM) in a time-dependent manner (12, 24, 48 or 72 h). They also used the anticancer drug RNVP-BEZ235, which is an inhibitor of PI3K and mTOR, to study the different effects of chloroquine. It was found that chloroquine had different effects depending on the dose used. For example, chloroquine at low doses (10-20 μM) rescues cell viability and acts as an autophagy inhibitor when used alone or with NVP-BEZ235. In contrast, chloroquine at high doses (40-160 μmol/L) promotes lysosomal membrane permeabilization and cell death[120].

Sulindac: The non-steroidal anti-inflammatory drug, sulindac, is defined as a cyclooxygenase inhibitor. As cell death and proliferation of cancer cell lines can be affected by a cyclooxygenase-independent mechanism, sulindac has been described as a promising anti-cancer repurposing agent[121]. In a study aimed at evaluating the dose effects of sulindac on CRC prevention, four different dosing regimens were applied to azoxymethane-treated mice. In the first dosing regimen, the researchers treated the mice with sulindac daily for 20 wk. In the second dosing regimen, the mice were treated with sulindac for 2 wk, treatment was discontinued for the next 2 wk, and this process was continued 5 times. In the third dosing regimen, sulindac was given to mice for 10 wk and then not given for 10 wk. A treatment regimen was not used in the last group and this was considered the control group. The first two sulindac regimens caused markedly lower final tumor counts compared to controls (P = 0.001). In addition, there was a significant decrease in tumor burden in all treatment groups compared with the control group. The study concluded that sulindac is a potential agent in the prevention of CRC when used especially in intermittent doses [122]. To investigate the effects of sulindac on CRC, a recent study treated C57B/6 Apcmin/+ mice with sulindac (30 mg/kg) for 3 wk. Moreover, the study hypothesized that the presence of phosphatidylcholine (PC) in sulindac treatment does not cause
Erlotinib is an antineoplastic agent used to treat non-small cell lung and gastrointestinal ulceration and bleeding, making use of the drug more convenient for the general population. Therefore, in addition to sulindac treatment, the researchers also treated mice with sulindac-PC (30 mg/kg). The results showed that treatment with sulindac or sulindac-PC significantly affected the polyp count. Sulindac treatment resulted in a 58% reduction in polyp count, while sulindac-PC resulted in a 64% reduction. In addition, the researchers confirmed their hypothesis and showed that treatment with sulindac-PC minimized gastrointestinal ulceration compared to treatment with sulindac alone[123].

**Mesalazine**: Mesalazine, also known as 5-aminosalicylic acid, is an anti-inflammatory drug used to treat patients with mild to moderate ulcerative colitis[124]. Since the risk of developing CRC is increased in patients with ulcerative colitis, researchers investigated whether this drug could be used for both therapeutic purposes. To evaluate the effects of mesalazine in CRC, HT29 CRC cells were treated with mesalazine at various concentrations for 3 d. It was found that mesalazine decreased cell proliferation and increased apoptosis of CRC cells. Treatment with mesalazine at a concentration of 20 mmol/L significantly decreased the number of CRC cells compared to controls. In addition, 30 mmol/L mesalazine decreased the number of HT29 cells by 50%. Increasing the concentration of mesalazine from 0 to 40 mmol/L also increased apoptosis. From these findings, the researchers concluded that mesalazine is a candidate drug for the prevention of CRC[125]. In another study, the HT29, Caco2, and HCT-116 cell lines were treated in a time- (24, 48, and 72 h) and dose- (0-50 mmol/L) dependent manner. It was revealed that 20 mmol/L or higher mesalazine concentrations significantly decreased cell proliferation at 72 h. Also, mesalazine concentrations above 35 mmol/L decreased cell proliferation even to baseline levels at 24 h. The researchers suggested that mesalazine causes cell cycle arrest and cell death in both a dose- and time-dependent manner, from which the researchers concluded that mesalazine may contribute to CRC prevention or treatment[126].

**Disulfiram**: Disulfiram is used to treat alcohol dependence[127]. To understand the effects of disulfiram in CRC, researchers applied disulfiram to parental colorectal cell lines as well as cell lines resistant to either oxaliplatin or SN-38. The addition of metal ions, particularly copper, to disulfiram is known to support and enhance the anticancer effects of disulfiram. Therefore, the researchers also combined disulfiram with copper and applied it to all cell lines. According to the cell viability assay, the combination of disulfiram with copper promoted the inhibition of cell viability. Moreover, the combination of disulfiram and copper with oxaliplatin or SN-38 resulted in inhibitory effects on the relevant resistant cell lines studied[128].

**Erlotinib**: Erlotinib is an antineoplastic agent used to treat non-small cell lung and pancreatic cancer[129]. A study conducted by Shi et al.[130] investigated the effect of erlotinib on CRC. The study included one hundred and thirty-two patients diagnosed with metastatic CRC who received the drug. Patients were divided into two groups depending on the drug regimen used. In the first group, patients were treated with bevacizumab and FOLFOX4 in 2-wk cycles, while in the second group they took erlotinib (100 mg) daily in addition to the bevacizumab-FOLFOX4 treatment combination. Patients were followed up for 3 years. Overall, the combination of the three drugs (bevacizumab, FOLFOX4, and erlotinib) improved progression-free survival and OS of metastatic CRC patients. A summary of the mentioned repurposed drugs is provided in Table 3.

**CONCLUSION**

In order to provide an updated vision of the key insights into CRC, we specifically reviewed systems biology studies on CRC. The incidence and mortality rates of CRC are high and more effective treatment options are required. Although most of the major cancer genes involved in CRC have been well characterized, the influence of additional factors in this disease remains undefined. Thus, the integration of different omics studies may provide new opportunities to reveal the mechanism of CRC. Parallel to the improvement in the molecular biology and systems biology techniques, more specific and sensitive biomarkers will improve the diagnosis of CRC at the early stages and hence, the prognosis of thousands of patients. Recent studies on CRC have focused on microbiota not only as biomarkers but also as a therapy option by improving drug response to traditional chemotherapeutics. Controlling microbiota
may also reduce dosages and the rate of drug administration resulting in improvement in the patient’s life quality. Although different omics studies from non-coding genes to metabolites have shown promising results which may be translated into the clinic in the foreseeable future, there is an urgent need for validation in larger populations. As with other cancers, an extensive part of research is based on drug discovery and the development of new therapies. In this study, we feature DR rather than drug discovery due to its many advantages. The less aggressive and more effective drugs may be redirected for CRC treatment via rational DR studies. In the future, repositioned drugs and their clinical implementation will increase the OS and quality of life of CRC patients.

REFERENCES

1 Sung H, Ferlay J, Siegel RL, Laversanne M, Soerjomataram I, Jemal A, Bray F. Global Cancer Statistics 2020: GLOBOCAN Estimates of Incidence and Mortality Worldwide for 36 Cancers in 185 Countries. CA Cancer J Clin 2021; 71: 209-249 [PMID: 33538338 DOI: 10.3322/caac.21660]

2 Douaiher J, Raviapati A, Grams B, Chowdhury S, Alatise O, Are C. Colorectal cancer-global burden, trends, and geographical variations. J Surg Oncol 2017; 115: 619-630 [PMID: 28194798 DOI: 10.1002/jso.24578]

3 Koncina E, Haan S, Rauh S, Letellier E. Prognostic and Predictive Molecular Biomarkers for Colorectal Cancer: Updates and Challenges. Cancers (Basel) 2020; 12 [PMID: 32019056 DOI: 10.3390/cancers12020319]

4 Moertel CG, Fleming TR, Macdonald JS, Haller DG, Laurie JA, Goodman PJ, Ungerleider JS, Emerson WA, Torney DC, Glick JH. Levamisole and fluorouracil for adjuvant therapy of resected colon carcinoma. N Engl J Med 1990; 322: 352-358 [PMID: 2300887 DOI: 10.1056/nejm199002083220602]

5 André T, Boni C, Mounedji-Boudiaf L, Navarro M, Tabernerio J, Hickish T, Topham C, Zaninelli M, Clingan P, Bridgewater J, Tabah-Fisch I, de Gramont A; Multicenter International Study of Oxaliplatin/5-Fluorouracil/Leucovorin in the Adjuvant Treatment of Colon Cancer (MOSAIc) Investigators. Oxaliplatin, fluorouracil, and leucovorin as adjuvant treatment for colon cancer. N Engl J Med 2004; 350: 2343-2351 [PMID: 15175436 DOI: 10.1056/NEJMoa032709]

6 Swiderska M, Choromańska B, Dąbrowska E, Konarzewska-Duchnowska E, Choromańska K, Szczurko G, Myśliwiec P, Dadan J, Ladny JR, Zwierz K. The diagnostics of colorectal cancer. Contemp Oncol (Pozn) 2014; 18: 1-6 [PMID: 24876814 DOI: 10.5114/wo.2013.39995]

7 Grassetto G, Caprici C, Marzola MC, Rampin L, Chondrogiannis S, Musto A, Crepaldi G, Minicozzi AM, Massaro A, Rubello D. Colorectal cancer: prognostic role of 18F-FDG-PET/CT. Abdom Imaging 2012; 37: 575-579 [PMID: 21847638 DOI: 10.1007/s00261-011-9789-7]

8 Alves Martins BA, de Bulhões GF, Cavalcanti IN, Martins MM, de Oliveira PG, Martins AM. Biomarkers in Colorectal Cancer: The Role of Translational Proteomics Research. Front Oncol 2019; 9: 1284 [PMID: 31828035 DOI: 10.3389/fonc.2019.01284]

9 Turanli B, Altay O, Bordin J, Turkez H, Nielsen J, Uhlen M, Arga Y, Mardinoglu A. Systems biology based drug repositioning for development of cancer therapy. Semin Cancer Biol 2021; 68: 47-58 [PMID: 31568815 DOI: 10.1016/j.semcancer.2019.09.020]

10 Xue H, Li J, Xie H, Wang Y. Review of Drug Repositioning Approaches and Resources. Int J Biol Sci 2018; 14: 1232-1244 [PMID: 30123072 DOI: 10.7150/ijbs.24612]

11 Kitano H. Systems biology: a brief overview. Science 2002; 295: 1662-1664 [PMID: 11872829 DOI: 10.1126/science.1069492]

12 Rai S, Raj U, Varadwaj PK. Systems Biology: A Powerful Tool for Drug Development. Curr Top Med Chem 2018; 18: 1745-1754 [PMID: 30360720 DOI: 10.2174/156802661866618012513226]

13 Cheasley D, Jorissen RN, Liu S, Tan CW, Love C, Palmieri M, Sieber OM. Genomic approach to translational studies in colorectal cancer. Transit Cancer Res 2015; 4: 235-255 [DOI: 10.3978/j.issn.2218-676X.2015.05.02]

14 Dalal N, Jalandra R, Sharma M, Prakash H, Makharia GK, Solanki PR, Singh R, Kumar A. Omics technologies for improved diagnosis and treatment of colorectal cancer: Technical advancement and major perspectives. Biomedi Pharmaco 2020; 131: 110648 [PMID: 33152902 DOI: 10.1016/j.biopharma.2020.110648]

15 Nambar Pr, Gupta RR, Misra V. An “omics” based survey of human colon cancer. Mutat Res 2010; 693: 3-18 [PMID: 20691711 DOI: 10.1016/j.mrfmmm.2010.07.008]

16 Wang K, Huang C, Nice EC. Proteomics, genomics and transcriptomics: their emerging roles in the discovery and validation of colorectal cancer biomarkers. Expert Rev Proteomics 2014; 11: 179-205 [PMID: 24611605 DOI: 10.1586/14789450.2014.894466]

17 Wan ML, Wang Y, Zeng Z, Deng B, Zhu BS, Cao T, Li YK, Xiao J, Han Q, Wu Q. Colorectal cancer (CRC) as a multifactorial disease and its causal correlations with multiple signaling pathways. Biosci Rep 2020; 40 [PMID: 32149326 DOI: 10.1042/BRS20200267]

18 Califf RM. Biomarker definitions and their applications. Exp Biol Med (Maywood) 2018; 243: 213-221 [PMID: 29405771 DOI: 10.1177/1535370217750088]

19 Zauber AG, Vinawer SJ, O’Brien MJ, Lansdorp-Vogelaar I, van Ballegooijen M, Hankey BF, Shi
Beklen H et al. Systems level CRC biomarkers and DR

W, Bond JH, Schaprio M, Panish JF, Stewart ET, Waye JD. Colonoscopic polypectomy and long-term prevention of colorectal-cancer deaths. N Engl J Med 2012; 366: 687-696 [PMID: 22356322 DOI: 10.1056/NEJMoa1100370]

Oh T, Kim N, Moon Y, Kim MS, Hoehn BD, Park CH, Kim TS, Kim NK, Chung HC, An S. Genome-wide identification and validation of a novel methylation biomarker, SDC2, for blood-based detection of colorectal cancer. J Mol Diagn 2013; 15: 498-507 [PMID: 23747712 DOI: 10.1016/j.jmoldx.2013.03.004]

Li D, Du Y, Zhang D, Wang LN, Yang C, Liu B, Wang WJ, Shi L, Hong WG, Zhang L, Yang YX. Identification of novel DNA methylation markers in colorectal cancer using MIRA-based microarrays. Oncol Rep 2012; 28: 99-104 [PMID: 22552777 DOI: 10.3892/or.2012.1779]

Moni Y, Olaru AV, Cheng Y, Agarwal R, Yang J, Luvsanjav D, Yu W, Selaru FM, Hutfless S, Lazarev M, Kwon JH, Brant SR, Marohn MR, Hutcheon DF, Duncan MD, Goel A, Meltzer SJ. Novel candidate colorectal cancer biomarkers identified by methylation microarray-based scanning. Endocr Relat Cancer 2011; 18: 465-478 [PMID: 21636702 DOI: 10.1530/ERC-11-0083]

Habermann JK, Bader FG, Franke C, Zimmermann K, Gemoll T, Fritzsche B, Ried T, Auer G, Bruch HP, Roblick UJ. From the genome to the proteome–biomarkers in colorectal cancer. Langenbecks Arch Surg 2008; 393: 93-104 [PMID: 17938952 DOI: 10.1007/s00423-007-0230-1]

Wang Z, Gerstein M, Snyder M. RNA-Seq: a revolutionary tool for transcriptomics. Nat Rev Genet 2009; 10: 57-63 [PMID: 19015660 DOI: 10.1038/nrg2484]

Ragusa M, Barbagallo C, Statellos L, Condorelli AG, Battaglia R, Tamburello L, Barbagallo D, Di Pietro C, Purrello M. Non-coding landscapes of colorectal cancer. World J Gastroenterol 2015; 21: 11709-11759 [PMID: 26556998 DOI: 10.3748/wjg.v21.i41.11709]

Slaby O, Svoboda M, Michalek J, Vyuzla R. MicroRNAs in colorectal cancer: translation of molecular biology into clinical application. Mol Cancer 2009; 8: 102 [PMID: 19912656 DOI: 10.1186/1476-4598-8-102]

Yamada A, Yu P, Lin W, Okugawa Y, Boland CR, Goel A. A RNA-Sequencing approach for the identification of novel long non-coding RNA biomarkers in colorectal cancer. Sci Rep 2018; 8: 575 [PMID: 29330370 DOI: 10.1038/s41598-017-18407-6]

Zhang Z, Jia H, Gu T, Hu Q, Yu J, Zang D, Song N, Wang H. RNA sequencing and bioinformatics analysis of the long noncoding RNA-mRNA network in colorectal cancer. J Cell Biochem 2018; 119: 9579-9596 [PMID: 30145796 DOI: 10.1002/jcb.27319]

Li XN, Wang JI, Ye CX, Zhao BC, Li ZL, Yang Y. RNA sequencing reveals the expression profiles of circRNA and indicates that circDDX17 acts as a tumor suppressor in colorectal cancer. J Exp Clin Cancer Res 2017; 37: 325 [PMID: 30591054 DOI: 10.1186/s13046-018-1006-x]

Ghanzarfar S, Fatima I, Aslam M, Musharraf SG, Sherman NE, Moskaluk C, Fox JW, Akhtar MW, Sadaf S. Identification of actin beta-like 2 (ACTBL2) as a novel, upregulated protein in colorectal cancer. J Proteomics 2017; 152: 33-40 [PMID: 27989943 DOI: 10.1016/j.jprot.2016.10.011]

Hao JJ, Zhi X, Wang Y, Zhang Z, Hao Z, Ye R, Tang Z, Qian F, Wang Q, Zhu J. Comprehensive Proteomic Characterization of the Human Colorectal Carcinoma Reveals Signature Proteins and Perturbed Pathways. Sci Rep 2017; 7: 42436 [PMID: 28181595 DOI: 10.1038/srep42436]

Quesada-Calvo F, Massot C, Bertrand V, Longuespér R, Béland N, Senjia J, Mazzucchelli G, Samadzadeh N, Bawir D, De Paon-Gillet MC, Delvenne P, Personse M, Corrozet Marques C, Pelusi M, De Paou E, Meuwis MA, Louis E. OLFM4, KNG1 and Sec24C identified by proteomics and immunohistochemistry as potential markers of early colorectal cancer stages. Clin Proteomics 2017; 14: 9 [PMID: 28344541 DOI: 10.1186/s12014-017-9143-3]

Yamamoto T, Kudo M, Peng WX, Takata H, Takakura H, Takeda K, Fujii T, Mitamura K, Taga A, Uchida E, Naito Z. Identification of aldolase A as a potential diagnostic biomarker for colorectal cancer based on proteomic analysis using formalin-fixed paraffin-embedded tissue. Tumour Biol 2016; 37: 13595-13606 [PMID: 27467821 DOI: 10.1007/s13277-016-5275-8]

Ilyas U, Zaman SU, Alfta R, Nadeem H, Muhammad SA. Genome wide meta-analysis of cDNA datasets reveals new target gene signatures of colorectal cancer based on systems biology approach. J Biol Res (Thessalon) 2020; 27: 8 [PMID: 32523911 DOI: 10.1007/s40709-020-00118-1]

Marcello M, Vymetalakova V, Neves RPL, Duran-Sanchon S, Vedeld HM, Tham E, van Dalum G, Flüggen G, García-Barberan V, Fijnenman RJ, Castells A, Vodicka P, Lind GE, Stockelheim NH, Heitzer E, Gironella M. Circulating biomarkers for early detection and clinical management of colorectal cancer. Mol Aspects Med 2019; 69: 107-122 [PMID: 31189073 DOI: 10.1016/j.mam.2019.06.002]

Ivanic MM, Megna BW, Sverchkov Y, Craven M, Reichelderfer M, Pickhardt PJ, Sussman MR, Kennedy GD. Noninvasive Detection of Colorectal Carcinomas Using Serum Protein Biomarkers. J Surg Res 2020; 246: 160-169 [PMID: 31586890 DOI: 10.1016/j.jss.2019.08.004]

Bhardwaj M, Gies A, Weigl K, Tikk K, Benner A, Schnitzel-King P, Borchers CH, Brenner H. Evaluation and Validation of Plasma Proteins Using Two Different Protein Detection Methods for Early Detection of Colorectal Cancer. Cancers (Basel) 2019; 11 [PMID: 31557860 DOI: 10.3390/cancers11011042]

Yu J, Zhai X, Li X, Zhong C, Guo C, Yang F, Yuan Y, Zheng S. Identification of MST1 as a potential early detection biomarker for colorectal cancer through a proteomic approach. Sci Rep 2017; 7: 14265 [PMID: 29079854 DOI: 10.1038/s41598-017-14539-x]

Fan NJ, Chen HM, Song W, Zhang ZY, Zhang MD, Feng LY, Gao CF. Macrophage mannose receptor 1 and S100A9 were identified as serum diagnostic biomarkers for colorectal cancer through...
a label-free quantitative proteomic analysis. *Cancer Biomark* 2016; 16: 235-243 [PMID: 26682511 DOI: 10.3233/CBM-150560]

40 **Peltier J**, Roperch JP, Audebert S, Borg JP, Camoin L. Quantitative proteomic analysis exploring progression of colorectal cancer: Modulation of the serpin family. *J Proteomics* 2016; 148: 139-148 [PMID: 27492143 DOI: 10.1016/j.jprot.2016.07.031]

41 **Matsubara J**, Honda K, Ono M, Sekine S, Tanaka Y, Kobayashi M, Jung G, Sakuma T, Nakamori S, Sata N, Nagai H, Ioka T, Okuaka T, Kosuge T, Tsuchida A, Shimahara M, Yasunami Y, Chiba T, Yamada T. Identification of adipophilin as a potential plasma biomarker for colorectal cancer using label-free quantitative mass spectrometry and protein microarray. *Cancer Epidemiol Biomarkers Prev* 2011; 20: 2195-2203 [PMID: 21828233 DOI: 10.1158/1055-9965.EPI-11-0400]

42 **Zhang A**, Sun H, Yan G, Wang P, Han Y, Wang X. Metabolomics in diagnosis and biomarker discovery of colorectal cancer. *Cancer Lett* 2014; 345: 17-20 [PMID: 24333717 DOI: 10.1016/j.canlet.2013.11.011]

43 **Ma Y**, Zhang P, Wang F, Liu W, Yang J, Qin H. An integrated proteomics and metabolomics approach for defining oncofetal biomarkers in the colorectal cancer. *Ann Surg* 2012; 255: 720-730 [PMID: 22395091 DOI: 10.1097/SLA.0b013e3182189a8b]

44 **Lin Y**, Ma C, Liu C, Wang Z, Yang J, Liu X, Shen Z, Wu R. NMR-based fecal metabolomics fingerprinting as predictors of earlier diagnosis in patients with colorectal cancer. *Oncotarget* 2016; 7: 29454-29464 [PMID: 27107423 DOI: 10.18632/oncotarget.8762]

45 **Gu J**, Xiao Y, Shu D, Liang X, Hu X, Xie Y, Lin D, Li H. Metabolomics Analysis in Serum from Patients with Colorectal Polyp and Colorectal Cancer by 1H-NMR Spectrometry. *Dis Markers* 2019; 2019: 3491852 [PMID: 31089393 DOI: 10.1155/2019/3491852]

46 **Nishiumi S**, Kobayashi T, Ikeda A, Yoshie T, Kibi M, Izumi Y, Okuno T, Hayashi N, Kawano S, Takenawa T, Azuma T, Yoshida M. A novel serum metabolomics-based diagnostic approach for colorectal cancer. *PLoS One* 2012; 7: e40549 [PMID: 22792336 DOI: 10.1371/journal.pone.0040549]

47 **Kim ER**, Kwon HN, Nam H, Kim JJ, Park S, Kim YH. Urine-NMR metabolomics for screening of advanced colorectal adenoma and early stage colorectal cancer. *Sci Rep* 2019; 9: 4786 [PMID: 30886205 DOI: 10.1038/s41598-019-41216-y]

48 **Wang Z**, Lin Y, Liang J, Huang Y, Ma C, Liu X, Yang J. NMR-based metabolic techniques identify potential urinary biomarkers for patients with colorectal cancer. *Oncotarget* 2017; 8: 105819-105831 [PMID: 29285295 DOI: 10.18632/oncotarget.22402]

49 **Uchiyama K**, Yagi N, Mizushima K, Higashimura Y, Hirai Y, Okamaya T, Yoshiida N, Katada K, Kamada K, Handa O, Ishikawa T, Takagi T, Konishi H, Kuriy Y, Nakamish M, Otsuji M, Etoh Y, Naito Y. Serum metabolomics analysis for early detection of colorectal cancer. *J Gastroenterol* 2017; 52: 677-694 [PMID: 27650200 DOI: 10.1007/s00535-016-1261-6]

50 **Liu HN**, Liu TT, Wu H, Chen YJ, Tseng YJ, Yao C, Weng SQ, Dong L, Shen XZ. Serum microRNA signatures and metabolomics have high diagnostic value in colorectal cancer using two novel methods. *Cancer Sci* 2018; 109: 1185-1194 [PMID: 29363233 DOI: 10.1111/cas.13514]

51 **Martín-Blázquez A**, Díaz C, González-Flores E, Franco-Rivas D, Jiménez-Luna C, Melguizo C, Prados J, Genilloud O, Vicente F, Caba O, Pérez Del Palacio J. Untargeted LC-HRMS-based metabolomics to identify novel biomarkers of metastatic colorectal cancer. *Sci Rep* 2019; 9: 20198 [PMID: 31882610 DOI: 10.1038/s41598-019-55952-8]

52 **Alomair AO**, Masoodi I, Alyamani EJ, Allehibi AA, Qutab AN, Alsayari KN, Altamami MA, Alshangheeti AS. Colonic Mucosal Microbiota in Colorectal Cancer: A Single-Center Metagenomic Study in Saudi Arabia. *Gastroenterol Res Pract* 2018; 2018: 5284754 [PMID: 29887882 DOI: 10.1155/2018/5284754]

53 **Kostic AD**, Gevers D, Pedamallu CS, Michaud M, Duke F, Earl AM, Ojesina AI, Jung J, Bass AJ, Díaz C, González-Flores E, Franco-Rivas D, Jiménez-Luna C, Melguizo C, Prados J, Genilloud O, Vicente F, Caba O, Pérez Del Palacio J. Untargeted LC-HRMS-based metabolomics to identify novel biomarkers of metastatic colorectal cancer. *Sci Rep* 2019; 9: 20198 [PMID: 31882610 DOI: 10.1038/s41598-019-55952-8]

54 **Beklen H** et al. Systems level CRC biomarkers and DR progression of colorectal cancer: Modulation of the serpin family. *J Proteomics* 2016; 148: 139-148 [PMID: 27492143 DOI: 10.1016/j.jprot.2016.07.031]

55 **Pellino G**, Gallo G, Pallante P, Capasso R, De Stefano A, Maretto I, Malapelle U, Qiu S, Nikolau S, Barina A, Clerico G, Reginelli A, Giuliani A, Sciaudone G, Kontovounisios C, Brunese L, Trompetto M, Selvaggi F. Noninvasive Biomarkers of Colorectal Cancer: Role in Diagnosis and Personalised Treatment Perspectives. *Gastroenterol Res Pract* 2018; 2018: 2397863 [PMID: 30008744 DOI: 10.1155/2018/2397863]

56 **Chen Y**, Li J, Yu X, Li S, Zhang X, Mo Z, Hu Y. APC gene hypermethylation and prostate cancer: a systematic review and meta-analysis. *Eur J Hum Genet* 2013; 21: 929-935 [PMID: 23299921 DOI: 10.1038/ejhg.2012.281]
Beklen H et al. Systems level CRC biomarkers and DR

59 Ting WC, Chen LM, Pao JB, Yang YP, You BJ, Chang TY, Lan YH, Lee HZ, Bao BY. Common genetic variants in Wnt signaling pathway genes as potential prognostic biomarkers for colorectal cancer. PLoS One 2013; 8: e56196 [PMID: 23405266 DOI: 10.1371/journal.pone.0056196]

60 Kandidoler D, Mittiböck M, Kappel S, Puhalla H, Herbst F, Langner C, Wolf B, Tschmelitsch J, Schüppinger W, Steger G, Hofbauer F, Samonigg H, Gianit M, Teley B, Kühner I; p53 Research Group and the Austrian Breast and Colorectal Study Group (ABCSG). TP53 Mutational Status and Prediction of Benefit from Adjuvant 5-Fluorouracil in Stage III Colorectal Cancer Patients. EBioMedicine 2015; 2: 825-830 [PMID: 26425688 DOI: 10.1016/j.ebiom.2015.06.003]

61 Pilat N, Grünberger T, Lángle F, Mittiböck M, Perisanidis B, Kappel S, Wolf B, Starling P, Kühner I, Mühlbacher F, Kandidoler D. Assessing the TP53 marker type in patients treated with or without neoadjuvant chemotherapy for resectable colorectal liver metastases: a p53 Research Group study. Eur J Surg Oncol 2015; 41: 683-689 [PMID: 25773284 DOI: 10.1016/j.ejso.2015.02.003]

62 Micu BV, Ancereou O, Vesa SC, Micu CM, Pop TR, Constantea N. The prognostic role of microsatellite instability in colorectal cancer patients. Ann Ital Chir 2017; 6: 425-432 [PMID: 28874631]

63 Romiti A, Rulli E, Pilozzi E, Gerardì C, Roberto M, Legramandi L, Falcone R, Pacchetti I, Marchetti P, Fioriani I. Exploring the Prognostic Role of Microsatellite Instability in Patients With Stage II Colorectal Cancer: A Systematic Review and Meta-Analysis. Clin Colorectal Cancer 2017; 16: e55-e59 [PMID: 27670891 DOI: 10.1016/j.clcc.2016.08.007]

64 Mizuno T, Cloyd JM, Vicente D, Omichi K, Chun YS, Kopetz S, Maru D, Conrad C, Tzeng CD, Wei SH, Aloia TA, Vauthy SJ, SMAD4 gene mutation predicts poor prognosis in patients undergoing resection for colorectal liver metastases. Eur J Surg Oncol 2018; 44: 684-692 [PMID: 29551247 DOI: 10.1016/j.ejso.2018.02.247]

65 Mei Z, Shao YY, Lin P, Cai X, Wang B, Ding Y, Ma X, Wu X, Xia Y, Zou D, Shu Y, Fu Z, Gu Y. SMAD4 and NF1 mutations as potential biomarkers for poor prognosis to cetuximab-based therapy in Chinese metastatic colorectal cancer patients. BMC Cancer 2018; 18: 479 [PMID: 29703253 DOI: 10.1186/s12885-018-4298-5]

66 de Cuba EM, Snejborjons P, Heidemann DA, van Grieken NC, Boschi LJ, Fijenman RJ, Belt E, Brii H, Stockmann HB, Hooijberg E, Punz CT, Koopman M, Nagtegaal ID, Coupé VH, Carvalho B, Meijer GA. Prognostic value of BRAF and KRAS mutation status in stage II and III microsatellite instable colon cancers. Int J Cancer 2016; 138: 1139-1145 [PMID: 26376292 DOI: 10.1002/ijc.29855]

67 Kadowaki S, Kakuta M, Takahashi S, Takahashi A, Arai Y, Nishimura Y, Yatsuoka T, Ook, A, Yamaguchi K, Matsuo K, Muro K, Akagi K. Prognostic value of KRAS and BRAF mutations in curatively resected colorectal cancer. World J Gastroenterol 2015; 21: 1275-1283 [PMID: 25632202 DOI: 10.3748/wjg.v21.i4.1275]

68 Nguyen MN, Choi TG, Nguyen DT, Kim JH, Jo YH, Shahid M, Akter S, Arayal SN, Yoo JH, Ahn YJ, Cho KM, Lee JS, Cho W, Kang I, Ha J, Kim SS. CRC-113 gene expression signature for predicting prognosis in patients with colorectal cancer. Oncotarget 2015; 6: 31674-31692 [PMID: 26937224 DOI: 10.18632/oncotarget.5183]

69 Zheng HT, Shi DB, Wang WY, Li XX, Xu Y, Tripathi P, Gu WL, Cai GX, Cai SJ. High expression of IncRNA MALAT1 suggests a biomarker of poor prognosis in colorectal cancer. Int J Exp Pathol 2014; 7: 3174-3181 [PMID: 25031737]

70 Ohtsuka M, Ling H, Ivan C, Pichler M, Matsushita D, Gobliirsc M, Stiegelbauer V, Shigeyasu K, Zhang X, Chen VM, Vidhu A, Bartholomew GA, Toyama Y, Kusunoki M, Doki Y, Mori M, Song S, Gunther KR, Krishnan S, Slaby O, Koel A, Radovich M, Calin GA. H19 Noncoding RNA, an Independent Prognostic Factor, Regulates Essential Rb-E2F and CDK8-β-Catenin Signaling in Colorectal Cancer. EBioMedicine 2016; 13: 113-124 [PMID: 27789274 DOI: 10.1016/j.ebiom.2016.10.026]

10 Han D, Gao X, Wang M, Qiao Y, Xu Y, Yang J, Dong N, He J, Sun Q, Lg V, Xu C, Tao J, Ma N. Long noncoding RNA H19 indicates a poor prognosis of colorectal cancer and promotes tumor growth by recruiting and binding to eIF4A3. Oncotarget 2016; 7: 22159-22173 [PMID: 26989025 DOI: 10.18632/oncotarget.8063]

12 Li Q, Dai Y, Wang F, Hou S. Differentially expressed long non-coding RNAs and the prognostic potential in colorectal cancer. Neoplasma 2016; 63: 977-983 [PMID: 27596298 DOI: 10.4149/neo_2016_617]

13 Li J, Du L, Yang Y, Wang C, Liu H, Wang L, Zhang X, Li W, Zheng G, Dong Z. MiR-429 is an independent prognostic factor in colorectal cancer and exerts its anti-apoptotic function by targeting SOX2. Cancer Lett 2013; 329: 84-90 [PMID: 23111103 DOI: 10.1016/j.canlet.2012.10.019]

14 Sun Y, Shen S, Liu X, Tang H, Wang Z, Yu Z, Li X, Wu M. MiR-429 inhibits cells growth and invasion and regulates EMT-related marker genes by targeting Oncue2 in colorectal carcinoma. Mol Cell Biochem 2014; 390: 19-30 [PMID: 24402783 DOI: 10.1007/s11010-013-1950-x]

15 Kandimalla R, Gao F, Matsuyama T, Ishikawa T, Uetake H, Takahashi N, Yamada Y, Bercera C, Kopetz S, Wang X, Goel A. Genome-wide Discovery and Identification of a Novel miRNA Signature for Recurrence Prediction in Stage I and III Colorectal Cancer. Clin Cancer Res 2018; 24: 3867-3877 [PMID: 29514841 DOI: 10.1158/1078-0432.CCR-17-3236]

16 Lovf M, Nome T, Bruun J, Enekaus R, Bakken AC, Mpinden JP, Rognum TO, Nesbakk A, Kallioniemi O, Lothe RA, Skotheim RD. A novel transcript, VNN1-AB, as a biomarker for colorectal cancer. Int J Cancer 2014; 135: 2077-2084 [PMID: 24687856 DOI: 10.1002/ijc.28855]
Carr SA, Lander ES, Golub TR. The Connectivity Map: using gene-expression signatures to connect A, Ross KN, Reich M, Hieronymus H, Wei G, Armstrong SA, Haggarty SJ, Clemons PA, Wei R, Repositioning. Yella JK

Innovation.

magnetic resonance (HR-MAS NMR) spectroscopy and gas chromatography mass spectrometry

Metabolic profiling of human colorectal cancer using high-resolution magic angle spinning nuclear

Chan EC

10.1158/1078-0432.CCR-13-1939

potential.

Jia W, Zheng S, Yen Y. A distinct metabolic signature of human colorectal cancer with prognostic

Qiu Y

Nicholson JK. 1H HR-MAS NMR spectroscopy of tumor-induced local metabolic "field-effects"

Jiménez B

10.1007/s11306-014-0758-3

Ulrich CM. Changes in urinary metabolic profiles of colorectal cancer patients enrolled in a

Res

Zhu D

24002600

recurrence in primary stage III and IV colorectal cancer.

Holstege FC, Jimenez CR, Fijneman RJ, Kranenburg OW, Rinkes IH. Maspin is a marker for early

AM, Piersma SR, Pham TV, Belt EJ, Bril H, Stockmann HB, Meijer GA, van Hillegersberg R,

4051-4058 [PMID: O15917892].

Sanchez E, Raghav K, Eng C, Chang GJ, Simon I, Bernards R, Overman M, Mills GB, Maru D,

Clarke CN

21465252

Carcinoembryonic Antigen (CEA) and Hepatic Metastasis in Colorectal Cancer: Update on

Campos-da-Paz M, Dórea JG, Galdino AS, Lacava ZGM, de Fatima Menezes Almeida Santos M. Carcinoembryonic Antigen (CEA) and Hepatic Metastasis in Colorectal Cancer: Update on Biomarker for Clinical and Biotechnological Approaches. Recent Pat Biotechnol 2018; 12: 269-279 [PMID: 30662978 DOI: 10.2174/1872208312666180731104244]

Gonzalez-Puns M, Cruz-Corrales M. Colorectal Cancer Biomarkers: Where Are We Now? Biomed Res Int 2015; 2015: 149014 [PMID: 26106999 DOI: 10.1155/2015/149014]

Li H, Zhao S, Jing Z, Li J, Shuanying Y, Zhang N. Combination of D-dimer and carcinoembryonic antigen levels as a predictive and prognostic biomarker in advanced colorectal cancer patients. J Cell Biochem 2018 [PMID: 30952316 DOI: 10.1002/jcb.29087]

Kirana C, Peng L, Miller R, Keating JP, Glenn C, Shi H, Jordan TW, M adden GJ, Stubbs RS. Combination of laser microdissection, 2D-DIGE and MALDI-TOF MS to identify protein biomarkers to predict colorectal cancer spread. Clin Proteomics 2019; 16: 3 [PMID: 30679934 DOI: 10.1186/s12191-019-0223-7]

van Huizen NA, Coebergh van den Braak RRJ, Doukas M, Dekker LJM, IJzermans JNM, Luiider TM. Up-regulation of collagen proteins in colorectal liver metastasis compared with normal liver tissue. J Biol Chem 2019; 294: 281-289 [PMID: 30409905 DOI: 10.1074/jbc.RA118.005087]

Mori K, Toiyama Y, Otake K, Fujikawa H, Saigusa S, Hiro J, Kobayashi M, Ohi M, Tanaka K, Inoue Y, Kobayashi Y, Kobayashi I, Mohri Y, Goel A, Kusunoki M. Proteomics analysis of differential protein expression identifies heat shock protein 47 as a predictive marker for lymph node metastasis in patients with colorectal cancer. Int J Cancer 2017; 140: 1425-1435 [PMID: 27925182 DOI: 10.1002/ijc.30557]

Mori K, Toiyama Y, Otake K, Ide S, Imaoka H, Okigami M, Okugawa Y, Fujikawa H, Saigusa S, Hiro J, Kobayashi M, Ohi M, Tanaka K, Inoue Y, Kobayashi Y, Mohri Y, Kobayashi I, Goel A, Kusunoki M. Successful identification of a predictive biomarker for lymph node metastasis in colorectal cancer using a proteomic approach. Oncotarget 2017; 8: 100955-100967 [PMID: 29291001 DOI: 10.18632/oncotarget.22149]

Jörgren F, Nilbert M, Rambech E, Bendahl PO, Lindmark G. Ezrin expression in rectal cancer predicts time to development of local recurrence. Int J Colorectal Dis 2012; 27: 893-899 [PMID: 22234584 DOI: 10.1007/s00053-011-1397-z]

Patara M, Santos EM, Coudry Rde A, Soares FA, Ferreira FO, Rossim BM. Ezrin expression as a prognostic marker in colorectal adenocarcinoma. Pathol Oncol Res 2011; 17: 827-833 [PMID: 21465252 DOI: 10.1007/s12253-011-9389-4]

Clarke CN, Lee MS, Wei W, Manyam G, Jiang ZQ, Ly U, Morris J, Broom B, Menter D, Vilasec Sanchez E, Raghav K, Eng C, Chang GJ, Simon I, Bernards R, Overman M, Mills GB, Maru D, Kopetz S. Proteomic Features of Colorectal Cancer Identify Tumor Subtypes Independent of Oncogenic Mutations and Independently Predict Relapse-Free Survival. Ann Surg Oncol 2017; 24: 4051-4058 [PMID: 28937990 DOI: 10.1245/s10434-017-6054-5]

Snoeren N, Emmink BL, Koerkamp MJ, van Hooff SR, Goos JA, van Houdt WJ, de Wit M, Prins AM, Piersma SR, Pham TV, Belt EJ, Bril H, Stockmann HB, Meijer GA, van Hillegersberg R, Holstege FC, Jimenez CR, Fijneman RJ, Krankenburg OW, Rinkes IH. Maspin is a marker for early recurrence in primary stage III and IV colorectal cancer. Br J Cancer 2013; 109: 1636-1647 [PMID: 24002600 DOI: 10.1038/bjc.2013.499]

Zhu D, Zhong Y, Wu H, Ye L, Wang J, Li Y, Wei Y, Ren L, Xu B, Xu J, Qin X. Predicting metastachronous liver metastasis from colorectal cancer using serum proteomic fingerprinting. J Surg Res 2013; 184: 861-866 [PMID: 23721930 DOI: 10.1016/j.jss.2013.04.065]

Liesenfeld DB, Habermann N, Toth R, Owen RW, Frei E, Staffa J, Schrotz-King P, Klika KD, Ulrich CM. Changes in urinary metabolic profiles of colorectal cancer patients enrolled in a prospective cohort study (ColoCare). Metabolomics 2015; 11: 998-1012 [PMID: 29250455 DOI: 10.1007/s11306-014-0758-3]

Jiménez B, Mímezami R, Kinross J, Cloarec O, Keun HC, Holmes E, Goldin RD, Ziprin P, Darzi A, Nicholson JK. 1H HR-MAS NMR spectroscopy of tumor-induced local metabolic "field-effects" enables colorectal cancer staging and prognostication. J Proteome Res 2013; 12: 959-968 [PMID: 23240862 DOI: 10.1021/pr3010106]

Qiu Y, Cai G, Zhou B, Li D, Zhao A, Xie G, Li H, Cai S, Xie D, Huang C, Ge W, Zhou Z, Xu LX, Jia W, Zheng S, Yen Y. A distinct metabolic signature of human colorectal cancer with prognostic potential. Clin Cancer Res 2014; 20: 2136-2146 [PMID: 24526730 DOI: 10.1158/1078-0432.CCR-13-1939]

Chan EC, Koh PK, Mal M, Cheah PY, Eu KW, Backshall A, Cavill R, Nicholson JK, Keun HC. Metabolic profiling of human colorectal cancer using high-resolution magic angle spinning nuclear magnetic resonance (HR-MAS NMR) spectroscopy and gas chromatography mass spectrometry (GC/MS). J Proteome Res 2009; 8: 352-361 [PMID: 19063642 DOI: 10.1021/pr8006323]

Arga KY. Interview with Prof. K. Yalçın Arga: A Pioneer of Multi-Omics Science and Health Care Innovation. OMICS 2019; 23: 460-462 [PMID: 31429661 DOI: 10.1089/omi.2019.0131]

Yella JK, Yaddanapudi S, Wang Y, Jegga AG. Changing Trends in Computational Drug Repositioning. Pharmaceuticals (Basel) 2018; 11 [PMID: 29874824 DOI: 10.3390/ph11020057]

Lamb J, Crawford ED, Peck D, Modell JW, Blat IC, Wrobel MJ, Lerner J, Brunet JP, Subramanian A, Ross KN, Reich M, Hieronymus H, Wei G, Armstrong SA, Haggarty SJ, Clemons PA, Wei R, Carr SA, Lander ES, Golub TR. The Connectivity Map: using gene-expression signatures to connect small molecules, genes, and disease. Science 2006; 313: 1929-1935 [PMID: 17088526 DOI: 10.1126/science.1134127]
Beklen H et al. Systems level CRC biomarkers and DR

10.1126/science.1132939

Lotfi Shahreza M, Ghadiri N, Moussavi SR, Varshosaz J, Green JR. A review of network-based approaches to drug repositioning. *Brief Bioinform* 2018; 19: 878-892 [PMID: 28334136 DOI: 10.1093/bib/bbx017]

Chung FH, Chiang YR, Tsang AL, Sung YC, Lu J, Huang MC, Ma N, Lee HC. Functional Module Connectivity Map (FMCM): a framework for searching repurposed drug compounds for systems treatment of cancer and an application to colorectal adenocarcinoma. *PLoS One* 2014; 9: e86299 [PMID: 24475102 DOI: 10.1371/journal.pone.0086299]

Hsieh YY, Chou CJ, Lo HL, Yang PM. Repositioning of a cycloxygenase inhibitor GW8510 as a ribonucleotide reductase M2 inhibitor to treat human colorectal cancer. *Cell Death Discov* 2016; 2: 16027 [PMID: 27551518 DOI: 10.1038/cddiscovery.2016.27]

Lliàres-Blanco J, Munteanu CR, Pazos A, Fernandez-Lozano C. Molecular docking and machine learning analysis of Abemaciclib in colon cancer. *BMC Cell Biol* 2020; 21: 52 [PMID: 32640984 DOI: 10.1186/s12860-020-00295-w]

Beklen H, Gulfidan G, Arga KY, Mardinoglu A, Turanli B. Drug Repositioning for P-Glycoprotein Mediated Co-Expression Networks in Colorectal Cancer. *Front Oncol* 2020; 10: 1273 [PMID: 32903699 DOI: 10.3389/fonc.2020.01273]

Wang YW, He SJ, Feng X, Cheng J, Luo YT, Tian L, Huang Q. Metformin: a review of its potential indications. *Drug Des Devel Ther* 2017; 11: 2421-2429 [PMID: 28860713 DOI: 10.2147/DDDT.S141675]

Jia Y, Ma Z, Liu X, Zhou W, He S, Xu X, Ren G, Xu G, Tian K. Metformin prevents DMH-induced colorectal cancer in diabetic rats by reversing the warburg effect. *Cancer Med* 2015; 4: 1730-1741 [PMID: 26376762 DOI: 10.1002/cam4.521]

Sena P, Mancini S, Benincasa M, Mariani F, Palumbo C, Roncucci L. Metformin Induces Apoptosis and Alters Cellular Responses to Oxidative Stress in H29 Colon Cancer Cells: Preliminary Findings. *Int J Mol Sci* 2018; 19 [PMID: 29772687 DOI: 10.3390/ijms19051478]

Bishnoil R, Shah C, Schmit JM, Hoo J (Stephen). Metformin and stage IV colorectal cancer in elderly. *J Clin Oncol* 2018; 36: e15636-e15636 [DOI: 10.1200/jco.2018.36.15_suppl.e15636]

Chan AT, Giovannucci EL, Meyerhardt JA, Schernhammer ES, Curhan GC, Fuchs CS. Long-term aspirin use: past, present, and future. *Int J Mol Sci* 2019; 20: 914-923 [PMID: 16118381 DOI: 10.1001/jama.294.8.914]

Reddy BS, Wang CX, Kong AN, Khor TO, Zheng X, Steele VE, Kopelovich L, Rao CV. Prevention of azoxymethane-induced colon cancer by combination of low doses of atorvastatin, aspirin, and celecoxib in F344 rats. *Cancer Res* 2006; 66: 4542-4546 [PMID: 16618783 DOI: 10.1158/0008-5472.CAN-05-4428]

Flossmann E, Rothwell PM. British Doctors Aspirin Trial and the UK-TIA Aspirin Trial. Effect of aspirin on long-term risk of colorectal cancer: consistent evidence from randomised and observational studies. *Lancet* 2007; 369: 1603-1613 [PMID: 17499602 DOI: 10.1016/S0140-6736(07)60747-8]

Jin S, Wu X. Aspirin inhibits colon cancer cell line migration through regulating epithelial-mesenchymal transition via Wnt signaling. *Oncol Lett* 2019; 17: 4675-4682 [PMID: 30944655 DOI: 10.3892/ol.2019.10089]

Jafarzadeh A, Nematl M, Khorrampelazad H, Hassan ZM. Immunomodulatory properties of cimetidine: Its therapeutic potentials for treatment of immune-related diseases. *Int Immunopharmacol* 2019; 70: 156-166 [PMID: 30802678 DOI: 10.1016/j.intimp.2019.02.026]

Kelly MD, King J, Cherian M, Dweryhouse SJ, Finlay JG, Adams WJ, King DW, Lubowski DZ, Morris DL. Randomized trial of preoperative cimetidine in patients with colorectal carcinoma with quantitative assessment of tumor-associated lymphocytes. *Cancer* 1999; 85: 1658-1663 [PMID: 10223557 DOI: 10.1002/1097-0248(19990415)85:8<1658::AID-CNCR3.3.CO;2-q>]

Kobayashi K, Matsumoto S, Morishima T, Kawabe T, Okamoto T. Cimetidine inhibits cancer cell adhesion to endothelial cells and prevents metastasis by blocking E-selectin expression. *Cancer Res* 2000; 60: 3978-3984 [PMID: 10919677]

Matsumoto S, Imaeda Y, Umemoto S, Kobayashi K, Suzuki H, Okamoto T. Cimetidine increases survival of colorectal cancer patients with high levels of sialyl Lewis-X and sialyl Lewis-A epitope expression on tumour cells. *Br J Cancer* 2002; 86: 161-167 [PMID: 11870500 DOI: 10.1038/sj.bjc.6600488]

Ali AH, Hale L, Yalamanchili B, Ahmed M, Zhou R, Wright SE. The Effect of Perioperative Cimetidine Administration on Time to Colorectal Cancer Recurrence. *Am J Thor* 2018; 25: e405-e411 [PMID: 29650589 DOI: 10.1097/MJT.0000000000000547]

Altman R, Bosch B, Brune K, Patrignani P, Young C. Advances in NSAID development: evolution of diclofenac products using pharmaceutical technology. *Drugs* 2015; 75: 859-877 [PMID: 25963327 DOI: 10.1007/s40265-015-0392-z]

Pantziarka P, Sukhatme V, Bouche G, Meheus L, Sukhatme VP. Repurposing Drugs in Oncology (ReDO)-diclofenac as an anti-cancer agent. *Euronoedic* 2016; 10: 610 [PMID: 26823679 DOI: 10.3332/ecancer.2016.610]

Falkowski M, Skogstad S, Shahzidi S, Smedsrod B, Sveinbjörnsson B. The effect of cyclooxygenase inhibitor diclofenac on experimental murine colon carcinoma. *Anticancer Res* 2003; 23: 2303-2308 [PMID: 12894507]

Arisan ED, Ergül Z, Bozdag G, Rencüzoğulları Ö, Çoker-Gürkan A, Obakan-Yerlikaya P, Coşkun
Beklen H et al. Systems level CRC biomarkers and DR

D, Palavan-Ünsal N. Diclofenac induced apoptosis via altering PI3K/Akt/MAPK signaling axis in HCT 116 more efficiently compared to SW480 colon cancer cells. *Mol Biol Rep* 2018; 45: 2175-2184 [PMID: 30406888 DOI: 10.1007/s11033-018-4378-2]

118 Verbaanderd C, Maes H, Schaaf MB, Sukhatme VP, Pantziarka P, Sukhatme V, Agostinis P, Bouche G. Repurposing Drugs in Oncology (ReDO)-chloroquine and hydroxychloroquine as anti-cancer agents. *Eancermedicalsscience* 2017; 11: 781 [PMID: 29225688 DOI: 10.3332/ecancer.2017.781]

119 Sasaki K, Tsuno NH, Sunami E, Tsurita G, Okaji Y, Nishikawa T, Shuno Y, Hongo K, Hiyoshi M, Kaneko M, Kitayama J, Takahashi K, Nagawa H. Chloroquine potentiates the anti-cancer effect of 5-fluorouracil on colon cancer cells. *BMC Cancer* 2010; 10: 370 [PMID: 20630104 DOI: 10.1186/1471-2407-10-370]

120 Park D, Lee Y. Biphasic activity of chloroquine in human colorectal cancer cells. *Dev Reprod* 2014; 18: 225-231 [PMID: 25949192 DOI: 10.12717/devrep.2014.18.4.225]

121 Chennamaneni S, Zhong B, Lama R, Su B. COX inhibitors Indomethacin and Sulindac derivatives as antiproliferative agents: synthesis, biological evaluation, and mechanism investigation. *Eur J Med Chem* 2012; 56: 17-29 [PMID: 22940705 DOI: 10.1016/j.ejmech.2012.08.005]

122 Yang LP, McCormack PL. MMX® Mesalazine: a review of its use in the management of mild to moderate ulcerative colitis. *Drugs* 2011; 71: 221-235 [PMID: 21275447 DOI: 10.2165/11205870-000000000-00000]

123 Reinacher-Schick A, Schoeneck A, Graeven U, Schwarte-Waldhoff I, Schmiegel W. Mesalazine causes a mitotic arrest and induces caspase-dependent apoptosis in colon carcinoma cells. *Carcinogenesis* 2003; 24: 443-451 [PMID: 12663503 DOI: 10.1093/carcin/24.3.443]

124 Koelink PJ, Mieremet-Ooms MA, Corver WE, Wolanin K, Hommes DW, Lamers CB, Verspaget HW. 5-aminosalicylic acid interferes in the cell cycle of colorectal cancer cells and induces cell death modes. *Inflamm Bowel Dis* 2010; 16: 379-389 [PMID: 19774649 DOI: 10.1002/ibd.21086]

125 Gastfriend DR. A pharmaceutical industry perspective on the economics of treatments for alcohol and opioid use disorders. *Ann N Y Acad Sci* 2014; 1327: 112-130 [PMID: 25236185 DOI: 10.1111/nyas.12538]

126 Steuva J, Keinicke H, Nielsen SL, Jandu H, Bartek J, Brünner N. Repurposing disulfiram as a potential novel treatment of drug-resistant metastatic colorectal cancer. *Mol Cancer Ther* 2018; 17 [DOI: 10.1158/1535-7163.targ-17-a143]

127 Tang PA, Tsao MS, Moore MJ. A review of erlotinib and its clinical use. *Expert Opin Pharmacother* 2006; 7: 177-193 [PMID: 16433583 DOI: 10.1517/14656566.7.2.177]

128 Shi S, Lu K, Gao H, Sun H, Li S. Erlotinib in combination with bevacizumab and FOLFOX4 as second-line chemotherapy for patients with metastatic colorectal cancer. *Am J Cancer Res* 2017; 7: 1971-1977 [PMID: 28979818]
