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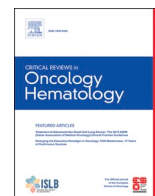
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The diverse molecular profiles of lynch syndrome-associated colorectal cancers are (highly) dependent on underlying germline mismatch repair mutations

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ABSTRACT

Lynch syndrome (LS) is a hereditary cancer syndrome that accounts for 3% of all new colorectal cancer (CRC) cases. Patients carry a germline pathogenic variant in one of the mismatch repair (MMR) genes (*MLH1*, *MSH2*, *MSH6* or *PMS2*), which encode proteins involved in a post-replicative proofreading and editing mechanism. The clinical presentation of LS is highly heterogeneous, showing high variability in age at onset and penetrance of cancer, which may be partly attributable to the molecular profiles of carcinomas. This review discusses the frequency of alterations in the WNT/B-CATENIN, RAF/MEK/ERK and PI3K/P TEN/AKT pathways identified in all four LS subgroups and how these changes may relate to the ‘three pathway model’ of carcinogenesis, in which LS CRCs develop from MMR-proficient adenomas, MMR-deficient adenomas or directly from MMR-deficient crypts. Understanding the specific differences in carcinogenesis for each LS subgroup will aid in the further optimization of guidelines for diagnosis, surveillance and treatment.

1. Introduction

Colorectal cancer (CRC) is the third most common type of cancer worldwide and the second leading cause of cancer-related death (Tiwari et al., 2016; Sinicrope, 2018; Siegel et al., 2019). Of all new CRC cases, 3% are attributable to Lynch syndrome (LS) (Tiwari et al., 2016; Sinicrope, 2018). The LS phenotype is mainly characterized by young-onset CRC, and amongst women, endometrial cancer (EC), but other extracolonic cancers may also develop (Lynch et al., 2015; Tamura et al., 2019). People with this syndrome carry a germline variant in one of the mismatch repair (MMR) genes, including *MLH1* (located at 3p22.2), *MSH2* (2p21), *MSH6* (2p16.3) and *PMS2* (7p22.2), or more rarely an

EPCAM deletion in the *a* gene that lies upstream of *MSH2* (for the extensive forms of all gene acronyms used within this article is referred to Supplementary Table 1) (Tiwari et al., 2016; Sinicrope, 2018; Lynch et al., 2015; Tamura et al., 2019; Peltomaki, 2016; Stojic et al., 2004).

Acting as a post-replicative proofreading and editing system, MMR prevents the accumulation of mutations that are generated by the slippage of DNA polymerases and otherwise overlooked by proofreading mechanisms (Tamura et al., 2019; Peltomaki, 2016; Weinberg, 2014). In addition, MMR recognizes and repairs diverse types of endogenous and exogenous damage, such as damage induced by oxidation (Bridge et al., 2014) or alkylation (Stojic et al., 2004). In short, MSH2 dimerizes either with MSH6 to form hMutSa, which scans DNA for base mismatches and

Abbreviations: COSM, Catalogue of Somatic Mutations in Cancer; COX-2, Cyclooxygenase 2; CRC, Colorectal cancer; EC, Endometrial cancer; EGFR, Epidermal growth factor receptor; EHTG, European Hereditary Tumour Group; FAP, Familial adenomatous polyposis; GSK-3 β , Glycogen synthase kinase-3 β ; IDL, Insertion-deletion loop; LS, Lynch syndrome; MAP, MUTYH-associated polyposis; MMR(d), Mismatch repair(deficient); MMR-DCF, MMR-deficient crypt foci; MSI, Microsatellite instability; MSS, Microsatellite stability; NF- κ B, Nuclear factor kappa-light-chain-enhancer of activated B cells; NGS, Next generation sequencing; NTHL1, Nth like DNA glycosylase 1; PGE₂, Prostaglandin E2; PI3K, Phosphatidylinositol 3-kinase; PIP2, Phosphatidylinositol-4,5-diphosphate; PIP3, Phosphatidylinositol-3,4,5-triphosphate; SCF, Skp1-Cdc53/Cullin-F-box-protein; SWI/SNF, SWItch/Sucrose Non-Fermentable; TSG, Tumour suppressor gene; WTX, APC membrane recruitment protein 1.

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short insertion-deletion loops (IDLs), or with MSH3 to form hMutSB, which recognizes longer IDLs (Tamura et al., 2019; Peltomaki, 2016). Upon localization of a mismatch, either hMutLa or hMutLy is recruited, consisting of MLH1 and PMS2 or MLH1 and MLH3, respectively. The hMutS-hMutL complex then triggers degradation of the strand containing the mismatch, followed by synthesis of a new strand (Tamura et al., 2019; Peltomaki, 2016; Weinberg, 2014). A deficient MMR (MMRd) system, as found in cells of LS patients who acquire a somatic hit in the remaining wild-type MMR allele, leads to a mutator phenotype and the development of microsatellite instability (MSI) (Peltomaki, 2003). The presence of MSI can be detected using DNA analysis, which together with immunohistochemical staining of the MMR proteins forms the basis for the identification of MMR deficiency. These two strategies show near-perfect concordance and have proven to be effective (Shia, 2008).

Genes that encode proteins with important cellular functions, including growth factor receptor genes (*TGFBR1*, *IGF1R*, *ACVR2A*), genes involved in apoptosis (*BAX*, *E2F4*) and transcription factors (*TCF4*) may harbour repetitive sequences that are known targets in MMRd tumours (Miyaki et al., 2001; Yamaguchi et al., 2006; Pinheiro et al., 2015). Mutations that disrupt the normal function of these genes may lead to abnormal differentiation, proliferation and cell survival. In addition, a MMRd system leads to an increased frequency of point mutations in non-repetitive sequences, involving a wide variety of oncogenes and tumour suppressor genes (TSGs) (Oliveira et al., 2004). Three signalling pathways frequently affected in LS CRCs are the WNT/B-CATENIN, the RAF/MEK/ERK and the PI3K/PTEN/AKT pathways, all of which aid in a cell's road to malignancy when in a deregulated state (Weinberg, 2014; White et al., 2012; Fearon, 2011).

The phenotype of LS is highly heterogeneous, an example of which is the wide variation in the penetrance of cancer between *MLH1*, *MSH2*, *MSH6* and *PMS2* variants. A recent prospective study reported that the cumulative risk to develop CRC by age 70 years is 46 % for *MLH1* carriers, compared to only 35 % for *MSH2* and 20 % for *MSH6* carriers (Moller et al., 2017). Several retrospective studies have reported that *PMS2* carrier risk is even lower (Suerink et al., 2019; Ten Broeke et al., 2018a). Furthermore, approximately 45 % of *MLH1*- and *MSH2*-associated CRCs occurring before the age of 75 develop as interval CRCs, whereas only 15 % of *MSH6*-associated CRCs and no *PMS2*-associated CRCs are reported interval cancers (Moller et al., 2018).

Despite this significant variation in phenotype, the need for gene-specific guidelines was only recently acknowledged, with the introduction of the European Hereditary Tumour Group (EHTG) (Seppala et al., 2020) and the guidelines published by the European Society of Gastrointestinal Endoscopy (ESGE) (van Leerdam et al., 2019). Meanwhile, the introduction of population-based LS screening has revealed even greater phenotypic heterogeneity, as population-based screening leads to an increase in the relative proportion of more mildly-affected LS families compared to LS testing based on stringent Amsterdam (Vasen et al., 1999) or Bethesda (Umar et al., 2004) criteria. Since *MSH6* and *PMS2* patients show a lower cancer penetrance, these patients were less likely to fulfil the earlier clinical criteria and therefore a large proportion of these patients were previously overlooked (Sinicrope, 2018). Another issue is that despite the known phenotypic heterogeneity of MMR genes, all diagnosed LS patients are screened for CRC every 1–2 years (Kohlmann and Gruber, 1993). Clearly, in view of the major differences between LS patient groups in the incidence of interval CRCs, optimal surveillance intervals are likely to differ between subgroups.

Much of the clinical heterogeneity seen in LS patients, such as wide variability in age of onset and cancer penetrance, can be attributed to the molecular profiles of individual carcinomas, for example due to the presence or absence of alterations in the three previously mentioned signalling pathways, which in part depends on which MMR gene is affected. It is important to stratify LS patients based on these molecular profiles, as this will facilitate the provision of optimal care to each patient.

Following the development of next generation sequencing (NGS), molecular profiles of large numbers of carcinomas can now be rapidly assessed, and this has led to a plethora of studies investigating the molecular profile of LS CRCs. In this review we evaluate available literature on NGS analyses of LS CRCs and analyse similarities and differences between the molecular profiles of *MLH1*-, *MSH2*-, *MSH6*-, and *PMS2*-associated CRCs. The main focus of this analysis is on alterations in the WNT/B-CATENIN, RAF/MEK/ERK and PI3K/PTEN/AKT pathways.

2. Alterations in the WNT/B-CATENIN pathway

The best studied signalling pathway in CRC is WNT/B-CATENIN. This pathway plays an important role in cellular development and differentiation, and was long thought to be the first pathway affected in the development of CRC (Weinberg, 2014; White et al., 2012; Brabletz et al., 2009). At the centre of this pathway is B-CATENIN, encoded by *CTNNB1* (Oliveira et al., 2004; Kohlmann and Gruber, 1993). In the absence of WNT signalling, B-CATENIN is bound to the cytoplasmic component of E-CADHERIN or is captured in a complex consisting of APC, AXIN, APC membrane recruitment protein 1 (WTX) and glycogen synthase kinase-3 β (GSK-3B) (Fig. 1A). The latter protein phosphorylates B-CATENIN, tagging it for destruction. However, when WNT binds to its receptors, known as FRIZZLED and LRP, a signalling cascade causes the shutdown of GSK-3B (Fig. 1B). This allows B-CATENIN levels to rise and B-CATENIN will then move to the nucleus, where it mainly interacts with the transcription factors TCF/LEF to influence proliferation and differentiation, in addition to other important processes (Weinberg, 2014; White et al., 2012; Brabletz et al., 2009).

The WNT/B-CATENIN pathway is important in CRC due to the major role of B-CATENIN signalling in confining enterocytes to the colonic crypts (Weinberg, 2014; Brabletz et al., 2009). Normally, enterocytes migrate out of the colonic crypts and die 3–4 days after they form. This prevents enterocytes from acquiring multiple mutations that might possibly lead to (pre-)malignancies. However, when the WNT/B-CATENIN pathway is overactive, high levels of B-CATENIN in the nucleus prevent outmigration of the enterocytes (Weinberg, 2014; White et al., 2012; Brabletz et al., 2009), allowing additional time for enterocytes to acquire mutations that may further stimulate carcinogenesis.

2.1. APC and CTNNB1

Overall, 90 % of CRCs have a disordered WNT/B-CATENIN pathway (White et al., 2012). Recent work by Ahadova et al. (2018, 2021), (Engel et al. (2020) and Ten Broeke et al. (2018b) showed that determining the frequencies of *APC* and *CTNNB1* mutations, which were already known to be frequently mutated in LS CRCs, is of particular value (Johnson et al., 2005; Miyaki et al., 1999). *APC* mutations are distributed across the gene and both alleles need to be affected, while *CTNNB1* shows gain-of-function mutations usually located in exon 3, an exon that encodes a regulatory domain normally phosphorylated by GSK-3B (Johnson et al., 2005). Ahadova et al. (2018) proposed that three distinct pathways explain CRC development in Lynch patients, in contrast to the widely accepted idea that mutations in the WNT/B-CATENIN pathway underlie all CRC development in LS. A long-held idea was that LS does not influence the initiation rate of adenomas, but simply accelerates the progression of existing adenomas to invasive cancer. It was thought that an adenoma initially develops independently of MMR deficiency, and at some point a somatic mutation in an MMR gene causes a second hit that initiates carcinogenesis (Fig. 2A). This pathway, also known as the Adenoma–Carcinoma pathway, has been challenged following the discovery of MMR-deficient crypt foci (MMR-DCF) (Shia et al., 2015; Kloor et al., 2012). Two new pathways initiated by MMR deficiency were then proposed (Ahadova et al. (2018)). MMR-DCFs can either form MMR-deficient adenomas when a second hit in a MMR gene is followed by, for example, two *APC*

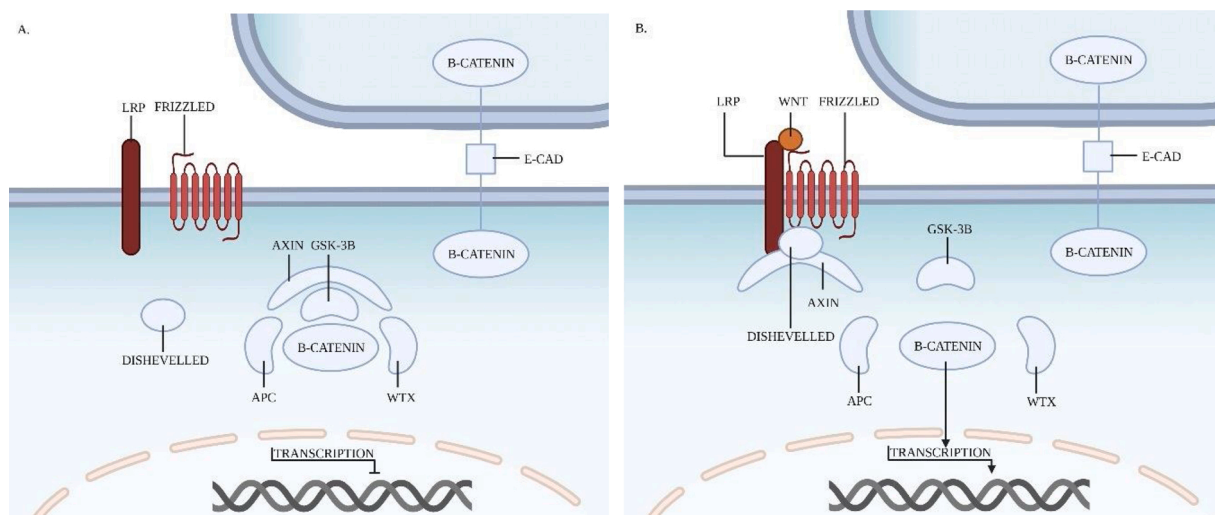


Fig. 1. WNT/B-CATENIN signaling pathway. (A) In the absence of a WNT signal, B-CATENIN is captured in a destruction complex consisting of APC, AXIN, WTX and GSK-3B. GSK-3B, in its active form, phosphorylates and thereby tags B-CATENIN for destruction. This mechanism prevents B-CATENIN from entering the nucleus and influencing transcription. In addition, B-CATENIN is bound to the cytoplasmic component of E-CADHERIN where it acts as an intermediary protein that links E-CADHERIN to the cytoskeleton. (B) When WNT proteins bind to their receptors, LRP and FRIZZLED, the DISHEVELLED and AXIN proteins are recruited to the membrane. This disrupts the destruction complex and inactivates GSK-3B, thereby giving B-CATENIN the opportunity to migrate to the nucleus and regulate the expression of genes involved in cell proliferation and differentiation.

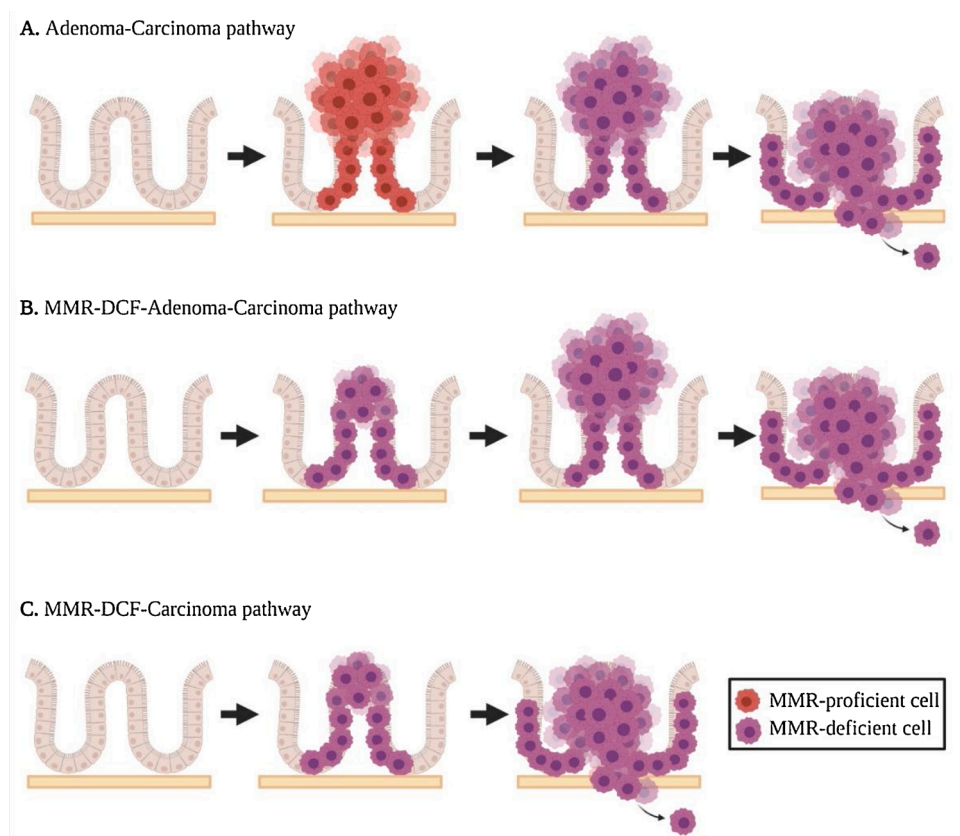


Fig. 2. Schematic overview of the three-pathway carcinogenesis model in LS. As hypothesized by Ahadova et al. (23), LS CRCs develop via three distinct pathways. In the Adenoma-Carcinoma pathway (A), adenomas develop independently of MMR deficiency. In contrast, in the MMR-DCF-Adenoma-Carcinoma pathway (B) and the MMR-DCF-Carcinoma pathway (C), tumour formation starts with MMR deficiency and is either followed by adenoma formation or results directly in a carcinoma.

mutations, which then progress to carcinomas (MMR-DCF-Adenoma-Carcinoma pathway), or they may form carcinomas directly (MMR-DCF-Carcinoma pathway), which show immediate invasive growth without a precursor lesion (Fig. 2B & C). The latter

pathway is presumed to result in nonpolypous cancer formation, which is difficult to detect using colonoscopic surveillance.

Tumours arising via the MMR-DCF-Carcinoma pathway pose a serious risk to patients since they can form rapidly and unnoticed and

can thus result in an interval carcinoma (Ahadova et al., 2018, 2021; Engel et al., 2020). Interestingly, (Ahadova et al., 2018) hypothesized that *CTNNB1* mutations are involved in nonpolypous carcinogenesis. This is in line with their previous work, which showed that LS CRCs harbouring *CTNNB1* mutations lack signs of polypous growth and have a comparable growth pattern, with immediate invasive growth (Ahadova et al., 2021). Although the association between *CTNNB1* mutations and nonpolypous growth was not significant (Ahadova et al., 2018), and the number of analysed *CTNNB1*-mutated LS CRCs was low (Ahadova et al., 2021), this hypothesis provides a logical explanation for the results of other studies (Moller et al., 2018; Ten Broeke et al., 2018b). A study performed by Ten Broeke et al. reported no *CTNNB1* mutations (0/20, 0%) in *PMS2*-associated CRCs (Ten Broeke et al., 2018b), whereas *MLH1*-associated CRCs carried a significant number of *CTNNB1* mutations (14/24, 58 %) (Table 1). This finding is particularly interesting in light of data from the Prospective Lynch Syndrome Database (www.plsd.eu), which demonstrated that *PMS2* carriers do not develop interval CRCs, whereas *MLH1* and *MSH2* carriers have a cumulative risk to develop interval CRCs before the age of 75 of approximately 45 % (Moller et al., 2018). Based on the facts that *PMS2* carriers do not show interval CRCs or carcinomas with *CTNNB1* mutations, while *MLH1* carriers show both, and that *APC* mutations appear to be less frequent in *MLH1*-associated cancers than in those associated with other MMR genes (Ahadova et al., 2018; Ten Broeke et al., 2018b), the following two conclusions can be drawn: first, since a significant percentage of *MLH1*-associated cancers harbour *CTNNB1* mutations, a sizeable proportion of all *MLH1*-associated CRCs must arise via the MMR-DCF–Carcinoma pathway. Secondly, the absence of *CTNNB1* mutations and the presence of *APC* mutations in *PMS2*-associated LS CRCs (Ahadova et al., 2018, 2021; Ten Broeke et al., 2018b) suggests that this pathway is of little importance in *PMS2* carriers, though studies in larger cohorts will be needed to confirm this.

The absence of interval CRCs may in fact contribute to the extremely low cancer penetrance observed in *PMS2* carriers under surveillance (Moller et al., 2017). Because all carcinomas arise from adenomas, which are effectively removed during surveillance colonoscopy, *PMS2* carriers have a low probability of developing interval cancers. As *MSH6* carriers also show a lower cancer penetrance, it is plausible to suppose that the molecular profile of *MSH6*- and *PMS2*-associated CRCs may be comparable. However, due to a paucity of data available on *MSH6*-associated CRCs, this remains a speculation at this time.

An alternative and generally accepted explanation for the lower penetrance of *PMS2* and *MSH6* variants is that MLH1 forms an alternative heterodimer with MLH3 or PMS1 in case of a *PMS2* deficiency,

Table 1
APC, *CTNNB1* and *RNF43* mutational frequencies in LS CRCs, stratified for germline variant.

	MLH1	MSH2	MSH6	PMS2	Study
APC	1/9 (11 %)	6/8 (75 %)	3/3 (100 %)	1/1 (100 %)	(Ahadova et al., 2018)
	3/24 (13 %)	6/18 (33 %)	N/A	6/20 (30 %)	(Ten Broeke et al., 2018b)
	8/9 (89 %)	1/8 (13 %)	0/3 (0%)	0/1 (0%)	(Ahadova et al., 2018)
CTNNB1	6/14 (43 %)	2/29 (7%)	0/3 (0%)	0/2 (0%)	(Ahadova et al., 2021)
	8/16 (50 %)	2/29 (7%)	0/3 (0%)	N/A	(Engel et al., 2020) ¹
	14/24 (58 %)	1/18 (6%)	N/A	0/20 (0%)	(Ten Broeke et al., 2018b)
RNF43	10/18 (56 %)	7/17 (41 %)	2/4 (50 %)	0/5 (0%)	(Fennell et al., 2018)

NOTE:

N/A. not applicable.

¹ CRCs analysed in (Engel et al., 2020) were also used in (Ahadova et al., 2018) and (Ahadova et al., 2021).

and that *MSH2* does the same with *MSH3* in case of *MSH6* deficiency (Peltomaki, 2016). This mechanism would still allow partial damage repair and thus limit the number of mutations that might otherwise lead to cancer. The interplay between the two ideas is interesting and it is possible that mutations accumulate more readily in cells of *MLH1* carriers compared to *PMS2* carriers due to the functional redundancy of *PMS2*, which might explain the difference in *CTNNB1* mutational frequencies (Ten Broeke et al., 2018b). However, due to a lack of studies of the mutational burden in these tumours, this hypothesis cannot yet be proven.

An alternative explanation would be that *CTNNB1* mutations are not a direct consequence of MMRd, but are attributable to another process, for example, resulting from a high selection pressure on WNT/B-CATENIN signalling in MMR-DCF, which at this point do not have an *APC* mutation, leading to loss of other components of the pathway. This idea is in line with a limited contribution of MMRd to *CTNNB1* mutation, as suggested by previous studies (Ahadova et al., 2018; Johnson et al., 2005). However, this probably does not explain the absence of *CTNNB1* mutations in *PMS2*-associated LS CRCs, since this would imply that *PMS2* carriers do not have MMR-DCF, an idea for which no evidence has been found.

While the association between *CTNNB1* mutations and interval CRCs appears valid, it does not explain observations in *MSH2* carriers. Various studies have shown that *MSH2*-associated CRCs have relatively few *CTNNB1* mutations compared to *MLH1*-associated cancers (Table 1) (Ahadova et al., 2018, 2021; Engel et al., 2020; Ten Broeke et al., 2018b). Nonetheless, *MSH2*-associated CRCs arise as interval CRCs at a frequency similar to those associated with *MLH1* (Moller et al., 2018). Ten Broeke et al. (2018b) suggested that *MSH2* carriers might require variants in additional genes in order to enter the MMR-DCF–Carcinoma pathway. This, in turn, raises the question of why *MSH2* carriers require contributions from additional genes while *MLH1* carriers do not. An alternative explanation is that the majority of *MSH2*-associated CRCs are formed not by the MMR-DCF–Carcinoma pathway but by the other two pathways, an idea in line with the observation that both adenomas and advanced adenomas are found significantly more frequently in *MSH2* carriers compared to *MLH1* carriers (Engel et al., 2020). One explanation of the high frequency of interval CRCs in *MSH2* carriers is that the MMR-DCF–Adenoma–Carcinoma pathway, in which cells are already genetically unstable early in the process, leads to cancer more rapidly than the Adenoma–Carcinoma pathway, in which the mutator phenotype is acquired at a later timepoint (Engel et al., 2020). According to this mechanism, tumours arising via the MMR-DCF–Adenoma–Carcinoma pathway already have a high mutational burden and might thus develop unnoticed, eventually appearing as interval CRCs. Therefore, in addition to the small percentage of *MSH2*-associated CRCs that acquire *CTNNB1* mutations and follow the MMR-DCF–Carcinoma pathway, a larger number of tumours arise via the MMR-DCF–Adenoma–Carcinoma pathway and contribute to the high number of interval CRCs in *MSH2* carriers.

2.2. *RNF43*

Another gene product involved in the WNT/B-CATENIN pathway and now receiving increasing attention is *RNF43*. *RNF43* is a TSG that encodes RNF43, a protein that negatively regulates WNT signalling by ubiquitinating the WNT receptors, FRIZZLED and LRP (Fennell et al., 2018; Giannakis et al., 2014; Sekine et al., 2017). Numerous mutations in *RNF43* were identified in CRCs only recently (Giannakis et al., 2014), and since most mutations involved small IDLs and the *RNF43* gene contains two mononucleotide repeats, it was hypothesized that these mutations might be related to MSI. This hypothesis was strengthened by the finding that these mutations were more common in MSI CRCs than MSS CRCs (Giannakis et al., 2014; Jo et al., 2015), and subsequently led to studies investigating *RNF43* in LS CRCs. Sekine et al. (2017) noticed that *RNF43* mutations seem to be exclusively present in MMR-deficient

adenomas and carcinomas, having not been found in MMR-proficient tissue. However, *RNF43* mutations occur in LS CRCs, although at a lower frequency than in sporadic MSI CRCs (Fennell et al., 2018; Sekine et al., 2017). Interestingly, *RNF43* mutations frequently co-occur with *APC* and *CTNNB1* mutations in LS patients, in contrast to sporadic CRCs (Giannakis et al., 2014; Sekine et al., 2017). Together with the fact that more *RNF43* mutations are found in *MLH1*-associated CRCs (56 %) compared to *MSH2*-associated CRCs (41 %) (Fennell et al., 2018), this could suggest that *RNF43* mutations are synergistic with *CTNNB1* mutations in the MMR-DCF-Carcinoma pathway, helping direct *MLH1*-deficient crypt foci towards this pathway while *MSH2*-deficient foci are less able to do so (Table 1). This, however, is currently only speculation and needs to be tested in further research.

3. Alterations in the RAS-regulated signalling pathways

3.1. KRAS

Along with the WNT/B-CATENIN pathway, several RAS-regulated signalling pathways, such as the RAF/MEK/ERK kinase pathway and the PI3K/PTEN/AKT kinase pathway, are involved in the pathogenesis of various cancers, including CRC (Weinberg, 2014). At the centre of these pathways is a protein named RAS (Fig. 3). RAS proteins are GTPases found in three distinct isoforms: K-RAS, N-RAS and H-RAS (Weinberg, 2014; Yaeger and Saltz, 2014). Activating mutations in *KRAS*, *NRAS* and *HRAS* lead to overactivity of the downstream RAS pathways, resulting in the upregulation of cell proliferation and survival, and impaired differentiation (Weinberg, 2014; Yaeger and Saltz, 2014; Furtado and Samowitz, 2017). Overall, *KRAS*, *NRAS* and *HRAS* mutations are found in 45 %, 5% and 0% of all CRCs, respectively (Yaeger and Saltz, 2014; Furtado and Samowitz, 2017). Understandably, most literature focuses on *KRAS*. *KRAS* mutations are found in both MMR-proficient and MMR-deficient CRCs, with a slightly higher percentage in MMR-proficient CRCs (59 % vs. 43 %) (Rajagopalan et al., 2002). Mutations in MMR-deficient CRCs mainly involve codons 12 and 13, which disrupt GTPase activity and lead to the constitutive activation of K-RAS (Weinberg, 2014). Multiple studies have reported that specific

hotspot mutations (G12D and G13D) occur more frequently in sporadic MSI and LS CRCs than in MSS sporadic CRCs (Ahadova et al., 2018; Ten Broeke et al., 2018b; Yaeger and Saltz, 2014; Kloth et al., 2016; Young et al., 2001), and in most cases these mutations occur after the onset of MMR deficiency. The latter became clear following the identification of the MMRd-associated unique combination of mutation types, depicted as the Catalogue of Somatic Mutations in Cancer (COSMIC) signature 6 (Ahadova et al., 2018), and by the presence of *KRAS* mutations in LS carcinomas but not in LS adenomas (Giannakis et al., 2014).

KRAS mutations seem to occur frequently in *MLH1*-, *MSH2*-, *MSH6*- and *PMS2*-associated CRCs (Table 2) (Oliveira et al., 2004; Ahadova et al., 2018; Ten Broeke et al., 2018b). In a study performed by (Oliveira et al., 2004), the frequency of *KRAS* mutations in *MSH6*- and *MSH2*-associated CRCs was significantly higher than in *MLH1*-associated CRCs. Although this finding has not been directly confirmed by the results of other studies (Ahadova et al., 2018; Ten Broeke et al., 2018b), it supports the idea that different groups of LS carriers develop cancer via different routes. This concept is further strengthened by the finding that the hotspot mutations G12D and G13D accounted for only

Table 2
KRAS, *BRAF* and *PIK3CA* mutational frequencies in LS CRCs stratified by germline variant.

	MLH1	MSH2	MSH6	PMS2	Study
KRAS	5/9 (56 %)	2/8 (25 %)	2/3 (67 %)	1/1 (100 %)	(Ahadova et al., 2018)
	7/24 (29 %)	7/18 (39 %)	N/A	10/20 (50 %)	(Ten Broeke et al., 2018b)
	29/91 (32 %)	29/61 (48 %)	5/6 (83 %)	N/A	(Oliveira et al., 2004)
	0/77 (0%)	0/34 (0%)	N/A	N/A	(Domingo et al., 2004)
BRAF	0/13 (0%)	0/7 (0%)	N/A	N/A	(Deng et al., 2004)
	8/24 (33 %)	7/18 (39 %)	N/A	5/20 (25 %)	(Ten Broeke et al., 2018b)

NOTE:
N/A. not applicable.

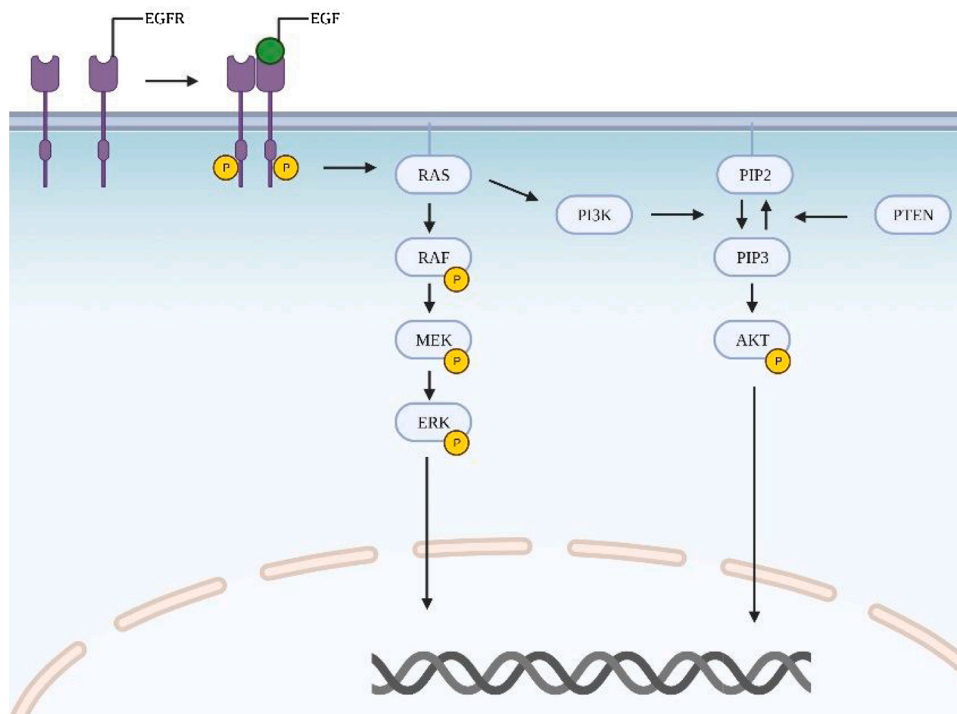


Fig. 3. The RAS-regulated signaling pathways. Upon binding of a growth factor, the growth factor receptor, in this example EGFR, dimerizes and each subunit phosphorylates its counterpart. The resulting phosphotyrosine residues serve as docking sites for a wide variety of proteins. These proteins can form a bridge between the receptor and RAS, located at the plasma membrane, leading to RAS activation. RAS, in turn, may activate several signaling pathways, including the RAF/MEK/ERK and PI3K/PTEN/AKT pathways. In the RAF/MEK/ERK pathway, RAS activates RAF, which then phosphorylates and thereby activates MEK. MEK phosphorylates ERK, which then phosphorylates substrates involved in various cellular processes, including transcription, proliferation and differentiation. In the PI3K/PTEN/AKT pathway, activation of PI3K by RAS leads to the conversion of PIP2 into PIP3. PIP3 activates the kinase AKT, which as in the case of ERK, phosphorylates proteins involved in various cellular processes. PTEN converts PIP3 into PIP2, effectively counteracting the actions of PI3K and serving as a negative regulator of the PI3K/PTEN/AKT pathway.

20 % of all *KRAS* mutations in *PMS2*-associated CRCs, whereas this figure was considerably higher in *MLH1*-, *MSH2*- and *MSH6*-associated CRCs (Ten Broeke et al., 2018b). The latter finding suggests that adenomas and/or CRCs in *PMS2* variant carriers acquire *KRAS* mutations before they develop *PMS2* deficiency, since types of mutations other than those related to MMR deficiency predominate (Ten Broeke et al., 2018b). Again, this is in line with the idea that *PMS2* carriers develop cancer only via the Adenoma–Carcinoma pathway, as discussed in previous sections, since *PMS2* deficiency apparently occurs as a late event and not as an initiating step. It also supports the hypothesis that *MSH2* deficiency can accelerate the adenoma-carcinoma pathway, explaining the observed interval carcinomas. Unfortunately, no data were available on the specific *KRAS* mutations found in *MSH6*-associated cancers (Ten Broeke et al., 2018b), as it would have been interesting to see if the G12D and G13D mutations were also less common in the *MSH6* subgroup, in line with the lower rate of interval cancers in *MSH6*.

3.2. *BRAF*

RAF is found directly downstream of *RAS* in the *RAF/MEK/ERK* pathway (Fig. 3) (Weinberg, 2014; Yaeger and Saltz, 2014). *B-RAF* is the isoform most commonly involved in cancer, and similarly to *KRAS* mutations, activating mutations in *BRAF* lead to continuous proliferation and disordered differentiation (Weinberg, 2014; Yaeger and Saltz, 2014; Thiel and Ristimäki, 2013). *B-RAF* is a serine/threonine kinase which phosphorylates and thereby activates downstream proteins, particularly *MEK* (Weinberg, 2014). V599E and V600E are two common mutations found in *BRAF*, and both result in a constitutively active protein kinase domain (Rajagopalan et al., 2002; Thiel and Ristimäki, 2013). In total, 5–10 % of CRCs have a *BRAF* mutation (Furtado and Samowitz, 2017). Although these mutations are relatively common in sporadic MMR deficiency and MSI (Rajagopalan et al., 2002; Nowak and Hornick, 2016), they are only rarely found in LS CRCs (Table 2) (Sekine et al., 2017; Rajagopalan et al., 2002; Domingo et al., 2004; Deng et al., 2004; Thiel and Ristimäki, 2013; Cohen et al., 2016). Moreover, *BRAF* and *KRAS* mutations are thought to be mutually exclusive (Yaeger and Saltz, 2014; Rajagopalan et al., 2002). Taken together, these data suggest that *BRAF* mutations have a minimal role in LS. As the *BRAF* V600E variant is strongly associated with somatic *MLH1* hypermethylation, many laboratories conduct *BRAF* analysis as a surrogate marker to assess *MLH1* hypermethylation (Parsons et al., 2012; Chen et al., 2014).

3.3. *PI3K* and *PTEN*

Another important pathway downstream of *RAS* is the *PI3K/PTEN/AKT* pathway (Fig. 3). In this pathway, *RAS* activates a phosphatidylinositol 3-kinase (*PI3K*), which then phosphorylates phosphatidylinositol-4,5-diphosphate (*PIP2*) to form phosphatidylinositol-3,4,5-triphosphate (*PIP3*) (Weinberg, 2014; Zhao and Vogt, 2008). *PIP3*, located at the plasma membrane, is mainly associated with the activation of *AKT/PKB*, which in turn activates a series of proteins that lead to cell proliferation, cell growth and resistance to apoptosis (Weinberg, 2014; Zhao and Vogt, 2008). One particular *PI3K*, *PIK3CA*, is involved in several types of cancer, including 15–25 % of all CRCs (Fearon, 2011). Activating mutations in *PIK3CA* leads to overproduction of *PIP3* and therefore unchecked cellular proliferation, growth and survival. Of note, these mutations are usually concurrent with either *KRAS* or *BRAF* mutations (Fearon, 2011; Yaeger and Saltz, 2014). This suggests that mutations in *KRAS* mainly effect the *RAF/MEK/ERK* pathway but have little or no impact on the *PI3K/PTEN/AKT* pathway, since additional *PIK3CA* mutations are required in order to impede the latter pathway (Fearon, 2011). Mutations in *PIK3CA* occur more frequently in MSI CRCs than in MSS CRCs (Kloth et al., 2016). When comparing the different subgroups of MSI CRCs, *PIK3CA* mutations appear more common in MMRd CRCs, in which both alleles of

a single MMR gene are somatically mutated, than in LS CRCs or *MLH1* hypermethylated CRCs (Cohen et al., 2016). When stratifying LS CRCs based on germline variants, *MLH1*-, *MSH2*- and *PSM2*-associated CRCs show no significant differences in *PIK3CA* status (Ten Broeke et al., 2018b), albeit additional literature to corroborate this observation is lacking and no data at all are available on *MSH6*-associated CRCs (Table 2).

Interestingly, *PIK3CA* mutations might be of importance when predicting the efficacy of aspirin as a preventive therapy in LS carriers. Aspirin has been shown to reduce the risk of CRC in the general population (Cook et al., 2013) and does this by inhibiting cyclooxygenase 2 (*COX-2*), which produces prostaglandin E2 (*PGE₂*) (Nguyen et al., 2020). *PGE₂* is involved in the regulation of cell proliferation and aids in tumorigenesis. A significant reduction in 10-year risk of developing CRC has now also been shown in LS patients (HR 0.65). It is not yet known whether cancers that develop during aspirin therapy have a specific molecular signature or whether the reduction in risk differs between *MLH1*-, *MSH2*- *MSH6*- or *PSM2*-LS patients (Burn et al., 2020).

Analysing the contribution of *PIK3CA* to this process might possibly generate new insights. The exact effects of *PIK3CA* variants on aspirin therapy in general are still controversial. Wang et al. (2015) demonstrated that *PGE₂* exerts its tumorigenic effects partly by activating the *PI3K/PTEN/AKT* pathway, which suggests that activating mutations in *PIK3CA* confer resistance to preventive aspirin therapy, as *PIK3CA* acts downstream of *PGE₂*. On the other hand, since *PIK3CA* signalling can result in the activation of nuclear factor kappa-light-chain-enhancer of activated B cells (*NF-κB*) (Wang et al., 2015), and because *NF-κB* induces transcription of the *COX2* gene (Dixon et al., 2013), increased *PIK3CA* signalling leads to increased synthesis of *PGE₂*, suggesting that pre-malignant cells with activating *PIK3CA* variants are actually susceptible to preventive aspirin therapy.

Acting in the opposite direction to *PIK3CA*, *PTEN* dephosphorylates *PIP3* to *PIP2* and thereby blocks the signalling pathway (Fig. 3) (Weinberg, 2014; Zhao and Vogt, 2008). *PTEN* is a TSG and inactivating mutations in both *PTEN* alleles provide a second mechanism by which the *PI3K/PTEN/AKT* pathway can become deregulated. Between 10 % and 20 % of CRCs carry *PTEN* mutations (Cohen et al., 2016; Laurent-Puig et al., 2009), with a higher prevalence in MSI CRCs compared to MSS CRCs (Cohen et al., 2016). As with *PIK3CA* mutations, *PTEN* mutations co-occur with *KRAS* and *BRAF* mutations (Fearon, 2011), providing further support for the idea that *KRAS* mutations alone are not able to activate the *PI3K/PTEN/AKT* pathway. Although *PTEN* mutations in LS EC are a hot topic, the exact role of *PTEN* mutations in LS CRCs remains to be investigated. In one study, 24 % (4 out of 18) of LS CRCs harboured a *PTEN* mutation (Cohen et al., 2016), indicating that *PTEN* mutations may play a role in a subset of CRCs associated with LS, though more research concerning the effect of these mutations is needed. No literature could be found regarding *PTEN* mutations in LS CRCs stratified for germline variants.

4. Other genes and their role in LS CRCs

4.1. *TP53*

TP53 is one of the best studied TSGs and is the most commonly mutated gene in all human cancers (Weinberg, 2014). The protein it encodes, *P53*, acts as a transcription factor and can impose cell cycle arrest and apoptosis in response to a wide variety of signals, including DNA damage (Weinberg, 2014). Mutations in *TP53* are found in 60 % of all CRCs (Nakayama and Oshima, 2019), with a higher prevalence in MSS CRCs compared to MSI CRCs (Kloth et al., 2016). The presence or absence of such mutations in LS CRCs could be very important because they have been associated with nonpolypous carcinogenesis and might therefore be involved in the MMR-DCF–Carcinoma pathway (Ahadova et al., 2018). If this is indeed the case, a higher frequency of *TP53* mutations would be expected in *MLH1*-associated and *MSH2*-associated LS

CRCs, since these carcinomas show the highest frequency of interval growth (Moller et al., 2018). However, this hypothesis is not directly supported by currently available literature, as significant numbers of *TP53* mutations have been found in LS CRCs associated with all four germline MMR mutations (Ahadova et al., 2018; Ten Broeke et al., 2018b). This topic therefore remains an important subject of investigation (Table 3). Using larger cohorts, it would be interesting to determine whether *TP53* mutations, like *CTNNB1* mutations, occur more frequently in *MLH1*-associated CRCs compared to *MSH2*-associated CRCs, as this would potentially shed more light on the preferential pathways of CRC development in *MLH1* versus *MSH2* carriers.

4.2. *FBXW7*

FBXW7, a member of the F-box protein family, is classified as a TSG and contributes to various types of cancer (Sailo et al., 2019; Yeh and Bellon, 2018). *FBXW7* encodes a protein that forms part of the Skp1-Cdc53/Cullin-F-box protein (SCF) complex, which functions as a ubiquitin ligase and controls the degradation of various oncoproteins including cyclin E, c-MYC and mTOR. Mutations in *FBXW7* that lead to a defective SCF complex cause the accumulation of oncoproteins and therefore promote tumorigenesis (Sailo et al., 2019; Yeh and Bellon, 2018). *FBXW7* is commonly mutated in CRC, at frequencies of 6–20% (Malapelle et al., 2016; Miyaki et al., 2009). Miyaki et al. (Miyaki et al., 2009) al. detected *FBXW7* mutations in 9% of LS CRCs and in 10% of sporadic CRCs, suggesting that *FBXW7* mutation frequencies are roughly similar between these groups. This contrasts with a study performed by ten Broeke et al. (Ten Broeke et al., 2018b), which found a significantly higher prevalence of *FBXW7* mutations in LS CRCs compared to sporadic CRCs (Table 3). In the latter study, 20% of *PMS2*-associated CRCs harboured *FBXW7* mutations, compared to 17% in *MLH1*- and *MSH2*-associated CRCs and 0% in sporadic CRCs. Since no significant differences were found between the LS subgroups, *FBXW7* most likely plays a similar role in each group, except possibly for *MSH6*-associated CRCs for which data are not available. Since alterations in *FBXW7* have been associated with both a poor prognosis (Korphaisarn et al., 2017; Iwatsuki et al., 2010) and an earlier onset of sporadic CRC (Kothari et al., 2016), it would be interesting to see if similar correlations can also be found between *FBXW7*-positive and *FBXW7*-negative LS CRCs.

4.3. *ARID1A*

ARID1A forms part of the highly conserved SWItch/Sucrose Non-Fermentable (SWI/SNF) chromatin-remodelling complex, which is a master regulator of transcription and acts as a tumour suppressor (Reisman et al., 2009). Mutations in *ARID1A* have been found in a range of cancer types and lead to a dysfunctional SWI/SNF complex (Reisman et al., 2009; Jones et al., 2012). The exact prevalence of *ARID1A* mutations in CRC remains to be validated, but is predicted to be around 10% (Jones et al., 2012). These mutations are strongly related to MMR deficiency and MSI (Jones et al., 2012; Ye et al., 2014; Cajuso et al., 2014; Chou et al., 2014), but the mechanism underlying this relationship remains a topic of discussion. *ARID1A* mutations could either be a

result of MMR deficiency or the cause. Evidence is currently lacking regarding the former option, as, for example, mutations in *ARID1A* are distributed along the entire gene rather than clustered at microsatellite regions (Cajuso et al., 2014). The latter option has already been considered for ECs (Bosse et al., 2013). In these cancers *ARID1A* mutations are associated not with LS but with *MLH1* hypermethylation (Bosse et al., 2013), based on the underlying idea that mutations in *ARID1A* cause epigenetic alterations that may include *MLH1* hypermethylation, indirectly causing MSI (Bosse et al., 2013). In the case of CRC, an association between *MLH1* hypermethylation and *ARID1A* loss has been demonstrated using immunohistochemistry (IHC) (Ye et al., 2014), suggesting that this mechanism might indeed also hold for CRC as well. Based on IHC, it has also been shown that CRCs lacking expression of *PMS2* only (n = 2), or both *MSH2* and *MSH6* (n = 9), lacked expression of *ARID1A*. In addition, 1 out of 4 carcinomas lacking expression of *MSH6* only, stained negative for *ARID1A* (Ye et al., 2014). Nevertheless, these results do not yet clarify the role of *ARID1A* in LS-associated CRC, and additional NGS analysis of large cohorts of LS CRCs will be needed to resolve this issue. In the course of these analyses it would be interesting to consider a possible association between *ARID1A* mutations and alterations in the PI3K/PTEN/AKT pathway. This idea arose because alterations in the PI3K/PTEN/AKT pathway are more commonly found in *ARID1A*-negative ECs, which may imply that *ARID1A* is associated with this pathway (Bosse et al., 2013). On the other hand, an inverse relationship between *TP53* and *ARID1A* mutations has been noted in endometrial (Bosse et al., 2013), ovarian (Xiao et al., 2012) and gastric (Cajuso et al., 2014) cancers, suggesting that *P53* and *ARID1A* mediate their tumour suppressor functions via roughly similar mechanisms.

5. Clinical implications and future recommendations

Patients with LS suffer from a hereditary predisposition to CRC. Before the introduction of the EHTG and ESGE guidelines in September 2020, in most countries all LS patients were screened and treated according to the same guidelines. As previously discussed, LS is considered to be a highly heterogeneous disease, with significant differences in, for example, the penetrance of cancer and the age at which cancer develops. A growing number of NGS analyses have also shown that most of this heterogeneity is attributable to a variety of different molecular pathways of tumour development, and only partly depends on which MMR gene is mutated. The varying distribution of mutations in important onco- and tumour suppressor genes supports the idea that LS can be divided into distinct subgroups, and furthermore suggests that in the future the diagnosis, surveillance and treatment of LS should be specifically optimized for each subgroup.

It is now recognized that LS CRCs develop via one of three pathways and that the relative occurrence of these pathways depends on the underlying germline MMR mutation. Combining available evidence, *CTNNB1* mutations appear to be associated with the MMR-DCF-Carcinoma pathway, while *APC* mutations are more closely related to the development of adenomas. In future experiments, it would be interesting to explore the mechanisms underlying these associations. Many questions regarding this topic still remain to be answered: Can functional redundancy account for the differences in *CTNNB1/APC* mutational frequencies between subgroups or is some other mechanism at play? Do *CTNNB1* mutations actually initiate the MMR-DCF-Carcinoma pathway? And what is the role of genes such as *RNF43* and *TP53* in this process? To answer these questions more research using larger cohorts is needed. Clarifying the mechanisms behind each pathway will not only lead to a better understanding of disease, but will also aid in the provision of optimal care to each patient. For example, changes in surveillance procedures might be beneficial, with shorter surveillance intervals for *MLH1* and possibly *MSH2* carriers, and longer intervals for *MSH6* and *PMS2* carriers. In addition, new insights could form a basis for subgroup-dependent treatments. Although MMRd CRCs, including LS CRCs, in general are known to be especially sensitive to

Table 3

TP53 and *FBXW7* mutational frequencies in LS CRCs stratified for germline variants.

	MLH1	MSH2	MSH6	PMS2	Study
TP53	4/9 (44%)	1/8 (13%)	1/3 (33%)	1/1 (100%)	(Ahadova et al., 2018)
	6/24 (25%)	5/18 (28%)	N/A	5/20 (25%)	(Ten Broeke et al., 2018b)
FBXW7	4/24 (17%)	3/18 (17%)	N/A	4/20 (20%)	(Ten Broeke et al., 2018b)

NOTE:

N/A. not applicable.

immunotherapies, considering the fact that the presence of MSI leads to a high mutational load with an increased expression of neoantigens, these therapies are not applicable to all LS patients, for example due to the high risk of immune-mediated adverse reactions (Chang et al., 2018). For this reason, the development of other therapies, such as molecular targeted therapies, is of vital importance as well. A recent study in mice for example showed that β -catenin short hairpin RNA therapy suppresses APC-mutated tumour growth but not CTNNB1-mutated tumour growth (Mologni et al., 2010). Extrapolating this outcome to humans, comparable results might be beneficial in patients with PMS2 variants but not in patients with MLH1 variants, highlighting the importance of specific care for each subgroup.

Although BRAF mutations do not seem to contribute to carcinogenesis in LS syndrome patients, the opposite is the case for KRAS, PIK3CA and PTEN mutations and might thus affect distinct LS subgroups in different ways. Knowing the status of KRAS, BRAF, PIK3CA and PTEN would also help in choosing the proper treatment. For example, PIK3CA mutations might influence the effectiveness of aspirin in preventing CRC, as mentioned earlier. Moreover, patients with metastatic CRC harbouring KRAS or BRAF variants show a poorer response to anti-EGFR therapies such as cetuximab and panitumumab (Raponi et al., 2008; Lievre et al., 2006). These monoclonal antibody therapies work by blocking epidermal growth factor receptors (EGFRs), which normally activate the RAS signalling pathways after the binding of a growth factor. Since KRAS and BRAF are downstream of the EGFR, blocking the EGFR will not prevent mutated KRAS or BRAF from signalling and therefore KRAS and BRAF status can be used to predict treatment response (Yaeger and Saltz, 2014; Furtado and Samowitz, 2017; Klothe et al., 2016; Seruca et al., 2009). A similar relationship is expected in the case of PIK3CA and PTEN, however, to date the use of PIK3CA and PTEN mutations to predict anti-EGFR therapy responses has produced conflicting results and thus requires further research (Furtado and Samowitz, 2017).

Besides genes involved in the WNT/B-CATENIN, RAF/MEK/ERK and PI3K/PTEN/AKT pathways, additional genes involved in other processes and signalling pathways are associated with CRC and LS. Amongst these are TP53, ARID1A and FBXW7, together with other genes that were not discussed in this review such as ERBB2, SMAD4, NF1, ATM, BRCA1/2 and CREBBP. For most of these genes, however, little research has been undertaken with regard to LS. A better understanding of the status of these genes in LS CRCs, with stratification for germline variant, will provide new insights in the development of CRC in LS patients and might also aid our understanding of the three pathways of carcinogenesis in LS patients.

One emerging development that could be especially helpful in future studies investigating the LS molecular profile is the extraction of mutational signatures from sequencing data (Alexandrov et al., 2013; Ma et al., 2018). Seven mutational signatures are associated with MMRd, including signatures 6 (already mentioned with regards to KRAS variants), 14, 15, 20, 21, 26 and 44 (Alexandrov et al., 2013; Helleday et al., 2014; Van Hoeck et al., 2019; Viel et al., 2017; Haradhvala et al., 2018; COSMIC, 2020). When analysing sporadic variants, looking at mutational signatures would make it easier to determine the timing of mutational events and to identify mutations attributable to a MMRd. Of note, these signatures are not only useful during research but also exhibit considerable potential in the diagnosis of LS. For example, signatures 6, 10, 15 and 26 indicate to be suitable for detecting MSI and as such can distinguish MMRd CRCs from MMR-proficient CRCs (Viel et al., 2017; Drost et al., 2017; Georgeson et al., 2020). Mutational signatures might also be used to detect hereditary predispositions by discriminating LS CRCs from sporadic MMRd CRCs. Recent studies focused on another DNA repair mechanism, base excision repair, demonstrated that deficiencies of Nth like DNA glycosylase 1 (NTHL1) correspond with the presence of signature 30 (Drost et al., 2017; Grolleman et al., 2019), while deficiencies of MUTYH result in signatures 18 and 36 (Viel et al., 2017; Pilati et al., 2017). This suggests that deficiencies within a single

repair mechanism can result in more than one signature.

In conclusion, the first steps in the molecular profiling of MLH1-, MSH2-, MSH6- and PMS2-associated CRCs have been taken, but further comprehensive genetic analysis of mutations in these cancers is vital in order to confirm the findings of previous studies and to provide a more complete picture of carcinogenesis in LS patients. Ultimately, our goal should be to use molecular profiles as guidance for surveillance, treatment, preventive strategies and other aspects of LS patient care.

Author contributions

Noah Cornelis Helderma: conceptualization, writing, visualization, investigation. **Sanne W. Bajwa - ten Broeke:** reviewing and editing. **Anne-Sophie van der Werf - 't Lam:** reviewing and editing. **Manon Suerink:** reviewing and editing. **Diantha Terlouw:** reviewing and editing. **Hans Morreau:** reviewing and editing. **Tom van Wezel:** reviewing and editing. **Maartje Nielsen:** conceptualization, supervision, reviewing and editing.

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Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.critrevonc.2021.103338>.

References

- Ahadova, A., Gallon, R., Gebert, J., Ballhausen, A., Endris, V., Kirchner, M., et al., 2018. Three molecular pathways model colorectal carcinogenesis in Lynch syndrome. *Int. J. Cancer* 143 (1), 139–150.
- Ahadova A., von Knebel Doeberitz M., Blaker H., Kloor M. CTNNB1-mutant colorectal carcinomas with immediate invasive growth: a model of interval cancers in Lynch syndrome. *Fam Cancer*. 15(4):579-586.
- Alexandrov, L.B., Nik-Zainal, S., Wedge, D.C., Aparicio, S.A., Behjati, S., Biankin, A.V., et al., 2013. Signatures of mutational processes in human cancer. *Nature* 500 (7463), 415–421.
- Bosse, T., ter Haar, N.T., Seeber, L.M., v Diest, P.J., Hes, F.J., Vasen, H.F., et al., 2013. Loss of ARID1A expression and its relationship with PI3K-Akt pathway alterations, TP53 and microsatellite instability in endometrial cancer. *Mod. Pathol.* 26 (11), 1525–1535.
- Brabletz, S., Schmalhofer, O., Brabletz, T., 2009. Gastrointestinal stem cells in development and cancer. *J. Pathol.* 217 (2), 307–317.
- Bridge, G., Rashid, S., Martin, S.A., 2014. DNA mismatch repair and oxidative DNA damage: implications for cancer biology and treatment. *Cancers (Basel)*. 6 (3), 1597–1614.

- Burn, J., Sheth, H., Elliott, F., Reed, L., Macrae, F., Mecklin, J.P., et al., 2020. Cancer prevention with aspirin in hereditary colorectal cancer (Lynch syndrome), 10-year follow-up and registry-based 20-year data in the CAPP2 study: a double-blind, randomised, placebo-controlled trial. *Lancet* 395 (10240), 1855–1863.
- Cajuso, T., Hanninen, U.A., Kondelin, J., Gylfe, A.E., Tanskanen, T., Katainen, R., et al., 2014. Exome sequencing reveals frequent inactivating mutations in ARID1A, ARID1B, ARID2 and ARID4A in microsatellite unstable colorectal cancer. *Int. J. Cancer* 135 (3), 611–623.
- Chang, L., Chang, M., Chang, H.M., Chang, F., 2018. Microsatellite Instability: A Predictive Biomarker for Cancer Immunotherapy. *Appl. Immunohistochem. Mol. Morphol.* 26 (2), e15–e21.
- Chen, D., Huang, J.F., Liu, K., Zhang, L.Q., Yang, Z., Chuai, Z.R., et al., 2014. BRAFV600E mutation and its association with clinicopathological features of colorectal cancer: a systematic review and meta-analysis. *PLoS One* 9 (3), e90607.
- Chou, A., Toon, C.W., Clarkson, A., Sioson, L., Houang, M., Watson, N., et al., 2014. Loss of ARID1A expression in colorectal carcinoma is strongly associated with mismatch repair deficiency. *Hum. Pathol.* 45 (8), 1697–1703.
- Cohen, S.A., Turner, E.H., Beightol, M.B., Jacobson, A., Gooley, T.A., Salipante, S.J., et al., 2016. Frequent PIK3CA mutations in colorectal and endometrial tumors with 2 or more somatic mutations in mismatch repair genes. *Gastroenterology* 151 (3), 440–447 e1.
- Cook, N.R., Lee, I.M., Zhang, S.M., Moorthy, M.V., Buring, J.E., 2013. Alternate-day, low-dose aspirin and cancer risk: long-term observational follow-up of a randomized trial. *Ann. Intern. Med.* 159 (2), 77–85.
- COSMIC, 2020. Catalogue of Somatic Mutations in Cancer [cited 2020 29 May]. Available from: <https://cancer.sanger.ac.uk/cosmic>.
- Deng, G., Bell, I., Crawley, S., Gum, J., Terdiman, J.P., Allen, B.A., et al., 2004. BRAF mutation is frequently present in sporadic colorectal cancer with methylated hMLH1, but not in hereditary nonpolyposis colorectal cancer. *Clin. Cancer Res.* 10 (1 Pt 1), 191–195.
- Dixon, D.A., Blanco, F.F., Bruno, A., Patrignani, P., 2013. Mechanistic aspects of COX-2 expression in colorectal neoplasia. *Recent Results Cancer Res.* 191, 7–37.
- Domingo, E., Laiho, P., Ollikainen, M., Pinto, M., Wang, L., French, A.J., et al., 2004. BRAF screening as a low-cost effective strategy for simplifying HNPCC genetic testing. *J. Med. Genet.* 41 (9), 664–668.
- Drost, J., van Boxtel, R., Blokzijl, F., Mizutani, T., Sasaki, N., Sasselli, V., et al., 2017. Use of CRISPR-modified human stem cell organoids to study the origin of mutational signatures in cancer. *Science* 358 (6360), 234–238.
- Engel, C., Ahadova, A., Seppala, T.T., Aretz, S., Bigirwamungu-Bargeman, M., Blaker, H., et al., 2020. Associations of pathogenic variants in MLH1, MSH2, and MSH6 with risk of colorectal adenomas and tumors and with somatic mutations in patients with lynch syndrome. *Gastroenterology* 158 (5), 1326–1333.
- Fearon, E.R., 2011. Molecular genetics of colorectal cancer. *Annu. Rev. Pathol.* 6, 479–507.
- Fennell, L.J., Clendenning, M., McKeone, D.M., Jamieson, S.H., Balachandran, S., Borowsky, J., et al., 2018. RNF43 is mutated less frequently in Lynch Syndrome compared with sporadic microsatellite unstable colorectal cancers. *Fam. Cancer* 17 (1), 63–69.
- Furtado, L.V., Samowitz, W.S., 2017. Colorectal cancer molecular profiling: from IHC to NGS in search of optimal algorithm. *Virchows Arch.* 471 (2), 235–242.
- Georgeson, P., Pope, B.J., Rosty, C., Clendenning, M., Walker, R., Mahmood, K., et al., 2020. Evaluating the utility of tumour mutational signatures for identifying hereditary colorectal cancer and polyposis syndrome carriers. *medRxiv*. 2019, 12.11.19014597.
- Giannakis, M., Hodis, E., Jasmine Mu, X., Yamauchi, M., Rosenbluh, J., Cibulskis, K., et al., 2014. RNF43 is frequently mutated in colorectal and endometrial cancers. *Nat. Genet.* 46 (12), 1264–1266.
- Grolleman, J.E., de Voer, R.M., Elsayed, F.A., Nielsen, M., Weren, R.D.A., Palles, C., et al., 2019. Mutational signature analysis reveals NTHL1 deficiency to cause a multi-tumor phenotype. *Cancer Cell* 35 (2), 256–266 e5.
- Haradhvala, N.J., Kim, J., Maruvka, Y.E., Polak, P., Rosebrock, D., Livitz, D., et al., 2018. Distinct mutational signatures characterize concurrent loss of polymerase proofreading and mismatch repair. *Nat. Commun.* 9 (1), 1746.
- Helleday, T., Eshtad, S., Nik-Zainal, S., 2014. Mechanisms underlying mutational signatures in human cancers. *Nat. Rev. Genet.* 15 (9), 585–598.
- Iwatsuki, M., Mimori, K., Ishii, H., Yokobori, T., Takatsuno, Y., Sato, T., et al., 2010. Loss of FBXW7, a cell cycle regulating gene, in colorectal cancer: clinical significance. *Int. J. Cancer* 126 (8), 1828–1837.
- Jo, Y.S., Kim, M.S., Lee, J.H., Lee, S.H., An, C.H., Yoo, N.J., 2015. Frequent frameshift mutations in 2 mononucleotide repeats of RNF43 gene and its regional heterogeneity in gastric and colorectal cancers. *Hum. Pathol.* 46 (11), 1640–1646.
- Johnson, V., Volikos, E., Halford, S.E., Eftekhari Sadat, E.T., Popat, S., Talbot, I., et al., 2005. Exon 3 beta-catenin mutations are specifically associated with colorectal carcinomas in hereditary non-polyposis colorectal cancer syndrome. *Gut* 54 (2), 264–267.
- Jones, S., Li, M., Parsons, D.W., Zhang, X., Wesseling, J., Kristel, P., et al., 2012. Somatic mutations in the chromatin remodeling gene ARID1A occur in several tumor types. *Hum. Mutat.* 33 (1), 100–103.
- Kloor, M., Huth, C., Voigt, A.Y., Benner, A., Schirmacher, P., von Knebel Doeberitz, M., et al., 2012. Prevalence of mismatch repair-deficient crypt foci in Lynch syndrome: a pathological study. *Lancet Oncol.* 13 (6), 598–606.
- Kloth, M., Ruessler, V., Engel, C., Koenig, K., Peifer, M., Mariotti, E., et al., 2016. Activating ERBB2/HER2 mutations indicate susceptibility to pan-HER inhibitors in Lynch and Lynch-like colorectal cancer. *Gut* 65 (8), 1296–1305.
- Kohlmann, W., Gruber, S.B., et al., 1993. Lynch syndrome. In: Adam, M.P., Ardinger, H. H., Pagon, R.A., Wallace, S.E., Bean, L.J.H., Stephens, K. (Eds.), *GeneReviews*(R). Seattle (WA).
- Korphaisarn, K., Morris, V.K., Overman, M.J., Fogelman, D.R., Kee, B.K., Raghav, K.P.S., et al., 2017. FBXW7 missense mutation: a novel negative prognostic factor in metastatic colorectal adenocarcinoma. *Oncotarget* 8 (24), 39268–39279.
- Kothari, N., Teer, J.K., Abbott, A.M., Srikumar, T., Zhang, Y., Yoder, S.J., et al., 2016. Increased incidence of FBXW7 and POLE proofreading domain mutations in young adult colorectal cancers. *Cancer* 122 (18), 2828–2835.
- Laurent-Puig, P., Cayre, A., Manceau, G., Buc, E., Bachet, J.B., Lecomte, T., et al., 2009. Analysis of PTEN, BRAF, and EGFR status in determining benefit from cetuximab therapy in wild-type KRAS metastatic colon cancer. *J. Clin. Oncol.* 27 (35), 5924–5930.
- Lievre, A., Bachet, J.B., Le Corre, D., Boige, V., Landi, B., Emile, J.F., et al., 2006. KRAS mutation status is predictive of response to cetuximab therapy in colorectal cancer. *Cancer Res.* 66 (8), 3992–3995.
- Lynch, H.T., Snyder, C.L., Shaw, T.G., Heinen, C.D., Hitchins, M.P., 2015. Milestones of Lynch syndrome: 1895–2015. *Nat. Rev. Cancer* 15 (3), 181–194.
- Ma, J., Setton, J., Lee, N.Y., Riaz, N., Powell, S.N., 2018. The therapeutic significance of mutational signatures from DNA repair deficiency in cancer. *Nat. Commun.* 9 (1), 3292.
- Malapelle, U., Pisapia, P., Sgariglia, R., Vigliar, E., Biglietto, M., Carlomagno, C., et al., 2016. Less frequently mutated genes in colorectal cancer: evidences from next-generation sequencing of 653 routine cases. *J. Clin. Pathol.* 69 (9), 767–771.
- Miyaki, M., Iijima, T., Kimura, J., Yasuno, M., Mori, T., Hayashi, Y., et al., 1999. Frequent mutation of beta-catenin and APC genes in primary colorectal tumors from patients with hereditary nonpolyposis colorectal cancer. *Cancer Res.* 59 (18), 4506–4509.
- Miyaki, M., Iijima, T., Shiba, K., Aki, T., Kita, Y., Yasuno, M., et al., 2001. Alterations of repeated sequences in 5' upstream and coding regions in colorectal tumors from patients with hereditary nonpolyposis colorectal cancer and Turcot syndrome. *Oncogene* 20 (37), 5215–5218.
- Miyaki, M., Yamaguchi, T., Iijima, T., Takahashi, K., Matsumoto, H., Mori, T., 2009. Somatic mutations of the CDC4 (FBXW7) gene in hereditary colorectal tumors. *Oncology* 76 (6), 430–434.
- Moller, P., Seppala, T., Bernstein, I., Holinski-Feder, E., Sala, P., Evans, D.G., et al., 2017. Cancer incidence and survival in Lynch syndrome patients receiving colonoscopic and gynaecological surveillance: first report from the prospective Lynch syndrome database. *Gut* 66 (3), 464–472.
- Moller, P., Seppala, T.T., Bernstein, I., Holinski-Feder, E., Sala, P., Gareth Evans, D., et al., 2018. Cancer risk and survival in path_MMR carriers by gene and gender up to 75 years of age: a report from the Prospective Lynch Syndrome Database. *Gut* 67 (7), 1306–1316.
- Mologni, L., Dekhil, H., Ceccon, M., Purgante, S., Lan, C., Cleris, L., et al., 2010. Colorectal tumors are effectively eradicated by combined inhibition of {beta}-catenin, KRAS, and the oncogenic transcription factor ITF2. *Cancer Res.* 70 (18), 7253–7263.
- Nakayama, M., Oshima, M., 2019. Mutant p53 in colon cancer. *J. Mol. Cell Biol.* 11 (4), 267–276.
- Nguyen, L.H., Goel, A., Chung, D.C., 2020. Pathways of colorectal carcinogenesis. *Gastroenterology* 158 (2), 291–302.
- Nowak, J.A., Hornick, J.L., 2016. Molecular evaluation of colorectal adenocarcinoma: current practice and emerging concepts. *Surg. Pathol. Clin.* 9 (3), 427–439.
- Oliveira, C., Westra, J.L., Arango, D., Ollikainen, M., Domingo, E., Ferreira, A., et al., 2004. Distinct patterns of KRAS mutations in colorectal carcinomas according to germline mismatch repair defects and hMLH1 methylation status. *Hum. Mol. Genet.* 13 (19), 2303–2311.
- Parsons, M.T., Buchanan, D.D., Thompson, B., Young, J.P., Spurdle, A.B., 2012. Correlation of tumour BRAF mutations and MLH1 methylation with germline mismatch repair (MMR) gene mutation status: a literature review assessing utility of tumour features for MMR variant classification. *J. Med. Genet.* 49 (3), 151–157.
- Peltomaki, P., 2003. Role of DNA mismatch repair defects in the pathogenesis of human cancer. *J. Clin. Oncol.* 21 (6), 1174–1179.
- Peltomaki, P., 2016. Update on Lynch syndrome genomics. *Fam. Cancer* 15 (3), 385–393.
- Pilati, C., Shinde, J., Alexandrov, L.B., Assie, G., Andre, T., Helias-Rodzewicz, Z., et al., 2017. Mutational signature analysis identifies MUTYH deficiency in colorectal cancers and adrenocortical carcinomas. *J. Pathol.* 242 (1), 10–15.
- Pinheiro, M., Pinto, C., Peixoto, A., Veiga, I., Lopes, P., Henrique, R., et al., 2015. Target gene mutational pattern in Lynch syndrome colorectal carcinomas according to tumour location and germline mutation. *Br. J. Cancer* 113 (4), 686–692.
- Rajagopalan, H., Bardelli, A., Lengauer, C., Kinzler, K.W., Vogelstein, B., Velculescu, V. E., 2002. Tumorigenesis: RAF/RAS oncogenes and mismatch-repair status. *Nature* 418 (6901), 934.
- Raponi, M., Winkler, H., Dracopoli, N.C., 2008. KRAS mutations predict response to EGFR inhibitors. *Curr. Opin. Pharmacol.* 8 (4), 413–418.
- Reisman, D., Glaros, S., Thompson, E.A., 2009. The SWI/SNF complex and cancer. *Oncogene* 28 (14), 1653–1668.
- Sailo, B.L., Bani, K., Girisa, S., Bordoloi, D., Fan, L., Halim, C.E., et al., 2019. FBXW7 in Cancer: What Has Been Unraveled Thus Far? *Cancers* (Basel). 11 (2).
- Sekine, S., Mori, T., Ogawa, R., Tanaka, M., Yoshida, H., Taniguchi, H., et al., 2017. Mismatch repair deficiency commonly precedes adenoma formation in Lynch Syndrome-Associated colorectal tumorigenesis. *Mod. Pathol.* 30 (8), 1144–1151.
- Seppala, T.T., Latchford, A., Negroi, I., Sampaio Soares, A., Jimenez-Rodriguez, R., Sanchez-Guillen, L., et al., 2020. European guidelines for the EHTG and ESCP for Lynch syndrome: an updated third edition of the Mallorca guidelines based on gene and gender. *Br. J. Surg.*

- Seruca, R., Velho, S., Oliveira, C., Leite, M., Matos, P., Jordan, P., 2009. Unmasking the role of KRAS and BRAF pathways in MSI colorectal tumors. *Expert Rev. Gastroenterol. Hepatol.* 3 (1), 5–9.
- Shia, J., 2008. Immunohistochemistry versus microsatellite instability testing for screening colorectal cancer patients at risk for hereditary nonpolyposis colorectal cancer syndrome. Part I. The utility of immunohistochemistry. *J. Mol. Diagn.* 10 (4), 293–300.
- Shia, J., Stadler, Z.K., Weiser, M.R., Vakiani, E., Mendelsohn, R., Markowitz, A.J., et al., 2015. Mismatch repair deficient-crypts in non-neoplastic colonic mucosa in Lynch syndrome: insights from an illustrative case. *Fam. Cancer* 14 (1), 61–68.
- Siegel, R.L., Miller, K.D., Jemal, A., 2019. Cancer statistics, 2019. *CA Cancer J. Clin.* 69 (1), 7–34.
- Sinicropo, F.A., 2018. Lynch syndrome-associated colorectal Cancer. *N. Engl. J. Med.* 379 (8), 764–773.
- Stojic, L., Brun, R., Jiricny, J., 2004. Mismatch repair and DNA damage signalling. *DNA Repair (Amst)*. 3 (8-9), 1091–1101.
- Suerink, M., Rodriguez-Gironde, M., van der Klift, H.M., Colas, C., Brugieres, L., Lavoine, N., et al., 2019. An alternative approach to establishing unbiased colorectal cancer risk estimation in Lynch syndrome. *Genet. Med.* 21 (12), 2706–2712.
- Tamura, K., Kaneda, M., Futagawa, M., Takeshita, M., Kim, S., Nakama, M., et al., 2019. Genetic and genomic basis of the mismatch repair system involved in Lynch syndrome. *Int. J. Clin. Oncol.* 24 (9), 999–1011.
- Ten Broeke, S.W., van der Klift, H.M., Tops, C.M.J., Aretz, S., Bernstein, I., Buchanan, D. D., et al., 2018a. Cancer risks for PMS2-Associated lynch syndrome. *J. Clin. Oncol.* 36 (29), 2961–2968.
- Ten Broeke, S.W., van Bavel, T.C., Jansen, A.M.L., Gomez-Garcia, E., Hes, F.J., van Hest, L.P., et al., 2018b. Molecular Background of Colorectal Tumors From Patients With Lynch Syndrome Associated With Germline Variants in PMS2. *Gastroenterology* 155 (3), 844–851.
- Thiel, A., Ristimaki, A., 2013. Toward a molecular classification of colorectal Cancer: the role of BRAF. *Front. Oncol.* 3, 281.
- Tiwari, A.K., Roy, H.K., Lynch, H.T., 2016. Lynch syndrome in the 21st century: clinical perspectives. *QJM* 109 (3), 151–158.
- Umar, A., Boland, C.R., Terdiman, J.P., Syngal, S., de la Chapelle, A., Ruschoff, J., et al., 2004. Revised Bethesda Guidelines for hereditary nonpolyposis colorectal cancer (Lynch syndrome) and microsatellite instability. *J. Natl. Cancer Inst.* 96 (4), 261–268.
- Van Hoeck, A., Tjoonk, N.H., van Boxtel, R., Cuppen, E., 2019. Portrait of a cancer: mutational signature analyses for cancer diagnostics. *BMC Cancer* 19 (1), 457.
- van Leerdam, M.E., Roos, V.H., van Hooft, J.E., Dekker, E., Jover, R., Kaminski, M.F., et al., 2019. Endoscopic management of polyposis syndromes: european Society of Gastrointestinal Endoscopy (ESGE) guideline. *Endoscopy* 51 (9), 877–895.
- Vasen, H.F., Watson, P., Mecklin, J.P., Lynch, H.T., 1999. New clinical criteria for hereditary nonpolyposis colorectal cancer (HNPCC, Lynch syndrome) proposed by the International Collaborative group on HNPCC. *Gastroenterology* 116 (6), 1453–1456.
- Viel, A., Bruselles, A., Meccia, E., Fornasari, M., Quaia, M., Canzonieri, V., et al., 2017. A specific mutational signature associated with DNA 8-Oxoguanine persistence in MUTYH-defective colorectal Cancer. *EBioMedicine* 20, 39–49.
- Wang, D., Fu, L., Sun, H., Guo, L., DuBois, R.N., 2015. Prostaglandin E2 promotes colorectal Cancer stem cell expansion and metastasis in mice. *Gastroenterology* 149 (7), 1884–1895 e4.
- Weinberg, R.A., 2014. *The Biology of Cancer*, 2nd ed. Garland Science.
- White, B.D., Chien, A.J., Dawson, D.W., 2012. Dysregulation of Wnt/beta-catenin signaling in gastrointestinal cancers. *Gastroenterology* 142 (2), 219–232.
- Xiao, W., Awadallah, A., Xin, W., 2012. Loss of ARID1A/BAF250a expression in ovarian endometriosis and clear cell carcinoma. *Int. J. Clin. Exp. Pathol.* 5 (7), 642–650.
- Yaeger, R., Saltz, L., 2014. Current and future roles in molecular profiling in colorectal Cancer. *Am. J. Hematol.* 10 (2), 18–24.
- Yamaguchi, T., Iijima, T., Mori, T., Takahashi, K., Matsumoto, H., Miyamoto, H., et al., 2006. Accumulation profile of frameshift mutations during development and progression of colorectal cancer from patients with hereditary nonpolyposis colorectal cancer. *Dis. Colon Rectum* 49 (3), 399–406.
- Ye, J., Zhou, Y., Weiser, M.R., Gonen, M., Zhang, L., Samdani, T., et al., 2014. Immunohistochemical detection of ARID1A in colorectal carcinoma: loss of staining is associated with sporadic microsatellite unstable tumors with medullary histology and high TNM stage. *Hum. Pathol.* 45 (12), 2430–2436.
- Yeh, C.H., Bellon, M., 2018. Nicot C. FBXW7: a critical tumor suppressor of human cancers. *Mol. Cancer* 17 (1), 115.
- Young, J., Simms, L.A., Biden, K.G., Wynter, C., Whitehall, V., Karamatic, R., et al., 2001. Features of colorectal cancers with high-level microsatellite instability occurring in familial and sporadic settings: parallel pathways of tumorigenesis. *Am. J. Pathol.* 159 (6), 2107–2116.
- Zhao, L., Vogt, P.K., 2008. Class I PI3K in oncogenic cellular transformation. *Oncogene* 27 (41), 5486–5496.

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