RAS signaling pathways, mutations and their role in colorectal cancer

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Abstract

Two of the main cellular pathways in which the RAS protein operates are the mitogen-activated protein kinases (MAPK) and phosphoinositide-3 kinase (PI3K) pathways. In a normal cell, these are important in controlling several functions, such as cell growth and survival. It becomes self-evident that these events will be disrupted in a malignant cell with a deregulated MAPK or PI3K pathway. Mutations in genes involved in these pathways and interacting with RAS, as well as RAS itself will be discussed. The second part of this review concentrates on how crucial RAS signaling is in colorectal cancer progression, with references to treatment response and prognosis when RAS or other related mutations are present.

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Key words: Genes; RAS; Colorectal neoplasms; Therapeutics; Mitogen-activated protein kinase signaling system

Core tip: This review outlines clearly the normal function of the mitogen-activated protein kinases and phosphoinositide-3 kinase cascades, in which the RAS proto-oncogene operates physiologically. It also describes the mutations in these pathways that lead to colorectal cancer (CRC), as well as other mutations outside these cascades affecting RAS function and also leading to CRC. The prognostic value of each mutation is assessed and linked to response rates to available biological treatments. Monoclonal antibodies under development are also briefly discussed.

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MITOGEN-ACTIVATED PROTEIN KINASES SIGNALING CASCADE

Two of the main cellular pathways in which the RAS protein operates are the mitogen-activated protein kinases (MAPK) and phosphoinositide-3 kinase (PI3K) pathways. In a normal cell, these are important in controlling several functions, such as cell growth and survival[1,2]. The first step towards activating this pathway occurs when a ligand binds to a receptor tyrosine kinase (RTK). For example, a well known ligand is epidermal growth factor (EGF), whose receptor is EGFR. Before being able to bind EGFR, EGF must first be released from the cell surface membrane where it resides. This is achieved by means of the TACE/ADAM-17 enzyme, which is particularly capable of cleaving transforming growth factor-α and amphiregulin, two of the ligands belonging to the EGF family[3]. Following ligand binding, the receptor becomes dimerised and phosphorylated[4]. Next, a complex of proteins is established within the cell, with growth factor receptor-bound protein 2 (GRB2) becoming attached to the receptor, whilst being bound by son of sevenless...
(SOS). Then the SOS protein, whilst still attached to GRB2, binds RAS as well. It should be noted here that there are several subtypes of the RAS protein, such as HRAS, NRAS and KRAS, but the most important one with regards to colorectal carcinogenesis is the latter, followed by NRAS⁶.

After the attachment of SOS to RAS, SOS shows guanine nucleotide exchange factor activity. This means that SOS is capable of displacing guanosine diphosphate (GDP) molecules from RAS and thus allowing guanosine triphosphate (GTP) molecules to bind and activate it. Active GTP-RAS is able to recruit the RAF proteins (A-RAF, B-RAF and C-RAF) to the cell surface. The RAF proteins are normally bound to, and therefore inhibited by, the 14-3-3 proteins in the cytosol. However, after binding to GTP-RAS, the RAF proteins are released from the 14-3-3 proteins and are therefore activated; they pair up amongst them and form heterodimers, which are then capable of binding and activating the KSR1 enzyme⁷.

The KSR1 enzyme is a relay hub connecting RAF heterodimers with the MEK protein. Hence, RAF proteins are able to phosphorylate and activate MEK, which in turn phosphorylates and activates ERK. ERK then enters the cell nucleus to activate a range of transcription factors, such as Jun and Fos[1]; these bind to the AP-1 DNA domain of the nucleus and transcribe genes involved in cell proliferation⁸.

The above process is entirely normal in a healthy cell, and is terminated by means of RAS-GTPase activating (GAP) proteins. As their name suggests, these proteins activate GTPase enzymes found within RAS, which hydrolyse GTP to GDP and therefore switch RAS off⁹.

### MUTATIONS RELATIVE TO THE MAPK PATHWAY

#### RAS mutations
One of the most frequent ways in which the MAPK is set to overdrive is by a mutation in the RAS protein; mutations in the KRAS protein are found in about 40% of all colorectal cancer (CRC) cases, whereas NRAS mutations are less common, having a frequency of 5%. Both in KRAS and NRAS, the most typical mutations are found at codons 12, most of the times, 13 and 61 (the latter being rarely affected). These mutations are sometimes present in early adenomas and in cells with minimal potential to develop a malignancy. However, they are also thought to enhance the malignant behaviour of cells with advanced CRC; both in vitro and animal studies indicate that silencing these mutated codons leads to attenuation of the tumorigenic growth properties of the affected cells⁸.

In molecular terms, mutations in these three KRAS/NRAS codons may lead to conformational changes so that the RAS-GAP protein cannot activate the inherent GTPase enzyme anymore. As a result, the GTP molecules are not hydrolysed and instead they maintain RAS continuously in its active state, thus causing protumorigenic effects by amplifying signaling in the MAPK pathway[3].

#### BRAF mutations
BRAF can also be mutated in the MAPK pathway, and this appears to happen in about 5%-10% of all colon cancer cases⁶. The commonest BRAF mutation amongst all cancers, including colorectal, is the V600E mutation. This occurs when adenine replaces thymine at nucleotide 1799. Consequently, glutamic acid (E) substitutes valine (V) at codon 600, hence the name of the mutation⁹.

Two basic models were proposed to explain how CRCs arise, and BRAF mutations occur in both of them. The first model proposed by Fearon and Vogelstein in 1990 suggested that CRC is a result of multiple adenomatous lesions progressing to carcinomas, following several somatic and inherited gene alterations[10]. Apparently, this is what happens in the majority of the cases[11].

In this model, the mutation of adenomatous polyposis coli (APC) leading to initial formation of the polypos is of paramount importance[12].

The second model, true in approximately 15% of all CRC cases[15], holds that CRC is caused by mutation of mismatch repair (MMR) genes, which normally fix errors in DNA replication. Hence the mutations result in replicative errors not being corrected and therefore microsatellites (short DNA repetitions) start accumulating or become abnormally short, leading to microsatellite instability (MSI[13]) and colorectal carcinogenesis. Inactivation of MMR genes can be observed in the hereditary nonpolyposis CRC (HNPPC) syndrome, but it usually occurs epigenetically; epigenetic inactivation most often involves the hypermethylation of MutL homolog 1 (MLH1), one of the MMR genes, and falls under a category of colorectal tumours called CpG island methylator phenotype (CIMP). CIMP tumours have a specific histological appearance, termed sessile serrated adenomas (SSAs). BRAF mutations are very frequent in SSAs, but not so frequent in HNPPC. Overall, they are mostly found amongst sporadic, high in MSI (MSI-H) colorectal tumours[8].

In any case, a BRAF mutation will lead to increased kinase activity and therefore increased downstream signaling in the MAPK cascade[13].

#### EGFR and other RTK mutations
EGFR (HER-1) gene amplifications or point mutations may cause an up-regulation of the receptor, thus increasing the probability of its activation by EGF binding and thus increasing signaling. However, such events are quite uncommon and appear in less than 5% of CRCs[16]. The human epidermal growth factor receptor 2 (HER-2)/neu receptor can also be overexpressed; though the evidence is inconsistent and ranges are anywhere between 0% and 83%, it is unlikely that this is a major determinant of colorectal tumorigenesis[13].

### PI3K SIGNALING CASCADE
The other main pathway in which RAS is involved is the
PI3K pathway. This is a very complex pathway, therefore only some of its key elements will be mentioned here. Just like in the case of the MAPK pathway, various growth factors initially bind on receptor tyrosine kinases, leading to their dimerisation and autophosphorylation. The next stage involves PI3Ks. There are three different classes of PI3Ks, but the most important class in human cancer is 1α. The regulatory subunit of this class, p85, attaches to phosphotyrosine residues and/or other adapters found on the RTKs. As a result, p110, the catalytic subunit of the PI3Ks is disinhibited and phosphorylates PIP2 to PIP3[8]. RAS can also activate the pathway physiologically by directly binding p110[9]. Conversely, the tumour suppressor protein PTEN dephosphorylates PIP3 back to PIP2, thus terminating signaling[8].

Once PIP3 is formed, it recruits PDK1 and AKT kinases and brings them in close proximity. PDK1 phosphorylates AKT. Consequently, AKT becomes activated and generates several signals, the details of which are probably unrelated to this topic. These signals essentially contribute to cellular growth and evasion of apoptosis[2].

**MUTATIONS RELATIVE TO THE PI3K PATHWAY**

**PIK3CA mutation**

PIK3CA is the gene encoding for P110α. Mutation of RAS often coexists with mutations at exons 9 and 20 of PIK3CA[10]. It has been hypothesised that, when RAS is mutated, it can no longer bind the physiological form of P110α efficiently. This necessitates the mutation of PIK3CA, which apparently will encode for a truncated version of P110α, on which the mutant RAS will be able to bind effectively. The estimated frequency of PIK3CA mutations in CRC is 15%-25%, and these may lead to increased PI3K activity[11].

**Phosphatase and tensin homolog mutation**

Nonsense mutations and deletions in the phosphatase and tensin homolog (PTEN) gene makes the PTEN protein unable to convert PIP3 to PIP2, thus it can no longer act as an antagonist to PI3K signaling. This mutation is cardinal to the manifestation of Cowden syndrome, as it appears in 85% of all its cases. Cowden syndrome is an autosomal dominant disorder that predisposes to multiple cancers, including colorectal. Overall, it is estimated that PTEN is mutated in 10%-20% of all CRC[8].

**OTHER MUTATIONS AFFECTING RAS SIGNALING**

**Neurofibromin 1 mutations**

The neurofibromin 1 (NF1) gene is responsible for causing the genetic disease neurofibromatosis type 1. NF1 acts as a negative regulator of RAS because it transcribes neurofibromin, a GAP, as mentioned above, these proteins hydrolyse RAS-bound GTP to GDP, therefore inactivating RAS. It has been suggested that NF1 may play a role in colorectal carcinogenesis when mutated, because it can no longer inhibit RAS signaling effectively. Indeed some studies have found increased NF1 mutations in malignant colorectal tissue[18,19], and in concurrence with KRAS mutations as well. Having said that, NF1 mutations may also occur with wild type KRAS. In addition, one study found that the majority of NF1 mutations were actually concurrent with BR-4F mutations, especially in MSI-H tumours[16]. Paradoxically, a more recent in vitro study observed that the mitogen-activated protein kinase (MAPK) pathway signaling was upregulated in malignant colorectal cells with wild type BR-4F and a knocked out NF1 gene[20]. Therefore, the role of NF1 in human colorectal carcinogenesis remains largely controversial.

The inverse relationship between CRC and neurofibromatosis type 1 is also evident; rarely, children with homozygous deficiency of the MLH1 gene, which leads to HNPCC, exhibit features of neurofibromatosis type 1[21].

**RASSF mutations**

The RASSF is a family of ten genes (RASSF1-10), members of which seem to act as tumour suppressors. An emerging body of evidence indicates that they can stimulate growth arrest and proapoptotic signals mediated by RAS. The exact way they achieve this is still unclear; there are suggestions that there is a domain in RASSF which can bind, and indeed this holds true to date for RASSF1, RASSF2, RASSF4 and RASSF5. RASSF1A is one of the most well studied members of the family[22], and it has been said that it either binds farnesylated KRAS directly[18,23] or it has to form a heterodimer with RASSF5 before is able to bind RAS[24].

Silencing of RASSF1A may occur when a specific sequence on the gene, the CpG island promoter region [i.e., a region rich in cytosine (C) and guanine (G) nucleobases linked by phosphodiester (p) bonds] is methylated. This event is regarded to be a major contributor to early CRC development, ranging from 12% to 81% amongst different studies. Methylation can also affect RASSF2 and RASSF5 in the context of CRC. Nevertheless, exactly how they bring about malignancy is currently under investigation[25].

**HOW IMPORTANT RAS SIGNALING IS FOR CRC**

In order to evaluate the importance of RAS signaling, it is reasonable to examine how RAS and associated mutations behave in the clinical setting; whether they respond to current treatments, and how good the prognosis is when such mutations are evident.

**Issues with KRAS**

Screening for KRAS mutation is the only widely used and accepted prognostic tool to decide eligibility for monoclonal antibody therapy[25,26]. This is largely because, the only molecular treatment currently licensed to be used in clinical practice is anti-EGFR therapy[26]. Hence, the
identification of a KRAS mutation is used as a means of exclusion from anti-EGFR therapy. The rationale for this is that since the MAPK pathway signaling is upregulated by a constitutively active KRAS protein, it is worthless to try and block the EGFR since MAPK signaling is no longer dependent on the activation of the receptor.

However, the above notion, though probably true most of the time, is not universally accepted. Although mutant KRAS, especially the G12V mutation, is often associated with poor response to anti-EGFR agents, some studies have not found the same results. Several clinical studies observed that patients with a p.G13D (codon 13) mutation in KRAS actually responded to treatment with cetuximab, as they had increased progression-free and overall survival compared to those on best supportive care or chemotherapy alone. This is a conclusion not to be ignored, because p.G13D positive patients are often refused administration of cetuximab (based on the rationale described above), albeit they could potentially benefit from it. Hence, further prospective clinical trials should be performed to confirm these data, since the value of the KRAS p.G13D mutation as a negative predictive biomarker is still contradictory.

In addition, regarding metastatic CRC, there is also a question of whether the primary or the metastatic lesion should be analysed for genetic mutations. Some researchers postulate that there is no difference between the two, whereas others report significant variations. It is also argued that the genetic profile of the metastatic lesion is what matters most, because it is the metastasis that causes the bulk of the morbidity and mortality related to the disease. These hypotheses may again have ethical implications. In a hypothetical scenario, a patient has a genetic variation between his primary and metastatic lesions; the majority of his metastatic cells carry the wild type KRAS gene, but the primary lesion has mutant alleles. Based on the latter, he is wrongfully denied potentially beneficial anti-EGFR therapy, if indeed the metastasis is what’s causing the major problem.

Finally, there is uncertainty regarding how many and which KRAS codons should be screened, as well as issues with cost-effectiveness.

Clinical status of other mutations

There are a great number of cases with wild type KRAS tumours which fail to respond to anti-EGFR therapy. This of course might happen because there are other mutations disrupting the MAPK pathway. These may include mutations in other regions of the KRAS gene which are not commonly tested. Indeed, the majority of clinical trials regarding KRAS mutations in CRC involved screening codons 12 and 13 only, whereas there are reported mutations in exons 3 and 4 as well. NRAS also becomes mutated occasionally.

BRAF mutation is associated with very poor prognosis as it does not respond to anti-EGFR therapy. In fact, in a study performed by Di Nicolantonio et al., it was observed that none of the patients with a V600E BRAF mutation responded to either cetuximab or panitumumab. BRAF mutations are also mutually exclusive with KRAS mutations, i.e., these two do not occur together. This means that if mutant KRAS is identified in a patient, there is no point of screening for BRAF as well. It is rather more useful to screen for KRAS first, since some particular mutations, as already discussed, may validate the use of anti-EGFR therapy. This is not the case for BRAF, where there is no response to monoclonal antibodies whatsoever. Hence, as a prognostic biomarker, BRAF can only be used to indicate complete insensitivity to anti-EGFR agents.

Contrary to BRAF, PIK3CA and PTEN are not mutually exclusive to KRAS. Loss of function of PTEN or mutation in PIK3CA is often associated with poorer response to cetuximab or panitumumab, as expected. However, there is no standard, reliable scoring system by which PTEN loss can be detected, thus making it an unsuitable prognostic biomarker. At the same time, the data regarding PIK3CA mutations is not uniform, as some studies report no overall difference in 5-year survival for patients with PIK3CA mutation, whilst others report positive response to cetuximab.

The future

Most patients responding well to current treatments are essentially those who only have EGFR upregulation. All the other mutations necessitate the discovery of agents that can block RAS signaling further down the pathway. Such a discovery will render any specific gene alteration irrelevant. Indeed, there has been a development of a RAF inhibitor, called PLX4032, which showed inhibition of RAF in melanoma, but had little success with CRC cells. Similarly, AZD6244, a MEK inhibitor which recently entered phase 2 trials for CRC showed no significant advantage over chemotherapy.

Conclusion

It has recently been said that the MAPK and PI3K cascades are important to carcinogenesis and progression of CRC. Apart from KRAS mutations, which are the main reason why anti-EGFR agents fail, several other genes related to RAS signaling also contribute to CRC manifestation and, some more than others, to anti-EGFR therapy insensitivity. If nothing else, KRAS and BRAF mutations can be used as negative biomarkers to identify patients who will not benefit from cetuximab and panitumumab. Nevertheless, as mentioned earlier, we do not know everything, as there are still several controversies in the data regarding the clinical status of some mutations, as in the case of p.G13D KRAS, PIK3CA and others. These indicate that there is a need to perform larger clinical trials that will minimise statistical error and will find out what exactly happens in these cases. In doing so, perhaps a deeper insight will be gained into the molecular mechanisms giving rise to CRC, thus allowing for pioneering pharmacological agents to be successfully developed.
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