**Name of Journals: *World Journal of Radiology***

**ESPS Manuscript NO: 27497**

**Manuscript Type: Minireviews**

**Mechanisms underlying 18F-fluorodeoxyglucose accumulation in colorectal cancer**

Kawada K *et al*. 18F-FDG accumulation and CRC

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**Author contributions:** Kawada K wrote the paper; Iwamoto M and Sakai Y contributed critical revision of the manuscript for important intellectual content.

**Conflict-of-interest statement:** The authors have no conflicts of interest to report.

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**Manuscript source:** Invited manuscript

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**Received:** June 1, 2016

**Peer-review started:** June 9, 2016

**First decision:** July 30, 2016

**Revised:** August 24, 2016

**Accepted:** September 13, 2016

**Article in press:**

**Published online:**

**Abstract**

Positron emission tomography (PET) with 18F-fluorodeoxyglucose (FDG) is a diagnostic tool to evaluate metabolic activity by measuring accumulation of FDG, an analogue of glucose, and has been widely used for detecting small tumors, monitoring treatment response and predicting patients’ prognosis in a variety of cancers. However, the molecular mechanism of FDG accumulation into tumors remains to be investigated. It is well-known that most cancers are metabolically active with elevated glucose metabolism, a phenomenon known as the Warburg effect. The underlying mechanisms for elevated glucose metabolism in cancer tissues are complex. Recent reports have indicated the potential of FDG-PET/CT scans in predicting mutational status (*e.g.*, *KRAS* gene mutation) of colorectal cancer (CRC), which suggests that FDG-PET/CT scansmay play a key role in determining therapeutic strategies by non-invasively predicting treatment response to anti-epidermal growth factor receptor (EGFR) therapy. In this review, we summarize the current findings investigating the molecular mechanism of 18F-FDG accumulation in CRC.

**Key words:** 18F-fluorodeoxyglucose-positron emission tomography; Colorectal cancer; Glucose metabolism; Mutational status; *KRAS*

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**Core tip:** Malignant cancers are preferential to metabolize glucose by glycolysis, even in the presence of oxygen, so-called Warburg effect. This elevated glucose metabolism is responsible for 18F-fluorodeoxyglucose (FDG) accumulation into cancer cells, which results in the positive signals in FDG-positron emission tomography scans. In spite of its clinical utility, the cellular and molecular mechanisms of 18F-FDG accumulation have not yet been elucidated. Here we review the current litarature published with respect to the mechnisms of 18F-FDG accumulation into colorectal cancer tissues.

Kawada K, Iwamoto M, Sakai Y. Mechanisms underlying 18F-fluorodeoxyglucose accumulation in colorectal cancer. *World J Radiol* 2016; In press

# INTRODUCTION

Positron Emission Tomography (PET) with 18F-fluorodeoxyglucose (FDG) is a imaging method used for detecting small tumors, monitoring treatment response and predicting patients’ prognosis in a variety types of cancers[1,2]. This technique is based on evaluating tissue glucose metabolism by　measuring accumulated FDG, a glucose analogue. FDG is incorporated into the cell through glucose transporters (GLUTs), and then phosphorylated by hexokinases (HXKs) to FDG-6-phosphate, which becomes stored within the cell. There is no standardized approach for quantitative measurement of 18F-FDG accumulation yet, although the 18F-FDG maximum standardized uptake value (SUVmax) is commonly considered as a barometer of tumor viability. In addition to SUVmax, there are some 18F-FDG uptake-related quantitative parameters: SUVmean (average SUV within the tumor), SUVpeak (peak SUV), metabolic tumor volume (MTV), total lesion glycolysis (TLG), *etc*.

Most cancer cells are preferential to metabolize glucose by glycolysis, even in the presence of oxygen, so-called “aerobic glycolysis (Warburg effect)”[3,4]. This increased glucose metabolism accounts for 18F-FDG accumulation into cancer cells, which results in the positive signals in FDG-PET/CT scans. However, the mechanisms how 18F-FDG is accumulated into cancer tissues are complex[5-7]. These factors are divided into tumor-related (*e.g.*, glucose metabolism, histological differentiation, vascular factor, tumor size and hypoxia) and non-tumor-related components (*e.g.*, high serum glucose level and local inflammation). 18F-FDG is not specifically accumulated into cancer; it can also be accumulated into inflammatory sites as well. In spite of its clinical usefulness, the cellular and molecular mechanisms of 18F-FDG accumulation have not yet been elucidated so far.

Colorectal cancer (CRC) is the third most common cancer and the fourth most common cause of cancer-related deaths in the world, with the majority attributable to distant metastases[8]. In spite of great advance in systemic treatment of metastatic CRC, the overall 5-year patient survival has remained lamentably low, below 10%. CRC is progressively promoted through multistep carcinogenesis of accumulated genetic changes in oncogenes and tumor suppressor genes. Most adenomas are initiated by inactivation of the *APC* gene, and then progress into adenocarcinomas through accumulation of additional alterations in the *KRAS*, *TP53* and *SMAD4* genes*, etc*[9].

In this context, this review summarizes the current literatures investigating the molecular mechanisms how 18F-FDG is accumulated into CRC.

**GLUCOSE TRANSPORTERS AND HEXOKINASES**

A line of literatures have demonstrated that 18F-FDG accumulation in cancer cells depends largely on two classes of proteins: Glucose transporters (GLUT) and Hexokinases (HXKs)[10]. 18F-FDG is incorporated into the cell via a family of 14 facilitative GLUTs, and then phosphorylated by HXKs to FDG-6-phosphate, which becomes stored within the cell, because of its negative charge. The up-regulation of GLUTs is commonly occurred in most cancers and is associated with poor prognosis of patients. Although different types of tumors have distinct expressions of different GLUTs, GLUT1 up-regulation is common in most cancers and is linked to tumor stage and prognosis[11,12]. In addition, increased levels of HXK (primarily, HXK2 of the 4 types) occur in many cancers[13,14]. HXK2 binds to the mitochondria membrane and efficiently phosphorylates FDG to FDG-6-phosphate. 18F-FDG accumulation depends largely on GLUT1 and the rate-limiting glycolytic enzyme, HXK2, in most types of cancers, although other GLUT proteins (*e.g.*, GLUT3) and other enzymes downstream of HXK (*e.g.*, pyruvate dehydrogenase kinase 1) may be involved[10]. While the combined expression of GLUT1 and HXK2 likely plays some role in determining 18F-FDG accumulation, the presence and strength of these associations seem to vary among tumor types, and conclusive evidence for one protein playing a dominant role is lacking. Although the molecular mechanisms of 18F-FDG accumulation into CRC are not as well-analyzed as in breast and lung cancers, several studies indicate that, in CRC, an increase of GLUT1 expression is more essential for 18F-FDG accumulation than HXK activity[10,15].

***KRAS***

***Mutations in the KRAS gene in CRCs***

Oncogenic activation of *KRAS* affects several cellular functions that regulate morphology, proliferation, and motility. *KRAS* mutations occur in a variety of human malignancies, most frequently in pancreatic cancer, non-small cell lung cancer (NSCLC) and CRCs. In particular, *KRAS* mutations occur in approximately 40% of CRCs; mutations of codon 12 or 13 occur in more than 90% of the cases. The *RAS* gene family encodes membrane-bound guanosine triphosphate (GTP) proteins that interact with several metabolic pathways, such as mitogen-activated protein kinase (MAPK) and phosphoinositide 3-kinase (PI3K). Activating *RAS* mutations alter the activity of GTPase, inducing constitutive activation of RAS pathway. A number of clinical studies indicate that *KRAS* mutations can predict a lack of response to anti-epidermal growth factor receptor (EGFR) therapy[16,17]. The anti-EGFR antibodies (cetuximab and panitumumab) are now recommended only for CRCs with wild-type *KRAS*, although a wild-type *KRAS* gene does not guarantee a response. Therefore, mutational testing of the *KRAS* gene, using biopsied or resected tissues, is incorporated into routine clinical practice. However, one limitation is the heterogeneity of *KRAS* mutational status, which can either be intratumoral heterogeneity within a primary CRC[18], or discordant *KRAS* status between a primary CRC and its corresponding metastatic CRC[19,20]. Another limitation is failure to judge *KRAS* status due to poor quality of extracted DNA. In addition, it is not always easy to extract the samples from metastatic CRCs due to limited access and invasive procedures. Therefore, alternative non-invasive tool to predict the mutation profile, such as 18F-FDG PET scans, could help overcome these limitations.

***Association between KRAS mutations and 18F-FDG accumulation***

There is recent preclinical evidence that *KRAS* mutations are associated with increased expression of GLUT1. Studies with isogeneic CRC cell lines indicated a significant increase in glucose uptake caused by GLUT1 up-regulation, which is prominent in CRC cells with mutant *KRAS* alleles, providing them with a growth advantage in low glucose environment[21]. In a retrospective analysis (*n* = 51), we previously found that SUVmax and tumor-to-liver ratio (TLR) were significantly higher in primary CRCs with mutated *KRAS* than in those with wild-type *KRAS*, and that SUVmax exhibited an odds ratio (OR) of 1.17 with an accuracy of 75% in predicting *KRAS* status when using a cutoff value of 13[22]. This was the first clinical report to show the causal relationship between *KRAS* mutations and 18F-FDG accumulation in a variety of cancer.

Following this report, some other groups have also shown that 18F-FDG accumulation can reflect *KRAS* mutational status in CRC and NSCLC (Table 1). Using a larger size of sample (*n* = 121), Chan *et al*[23] investigated the association between 18F-FDG uptake-related parameters and *KRAS* mutational status, and found that SUVmax and TW40% (a 40% threshold level of SUVmax for tumor width (TW) were 2 predictors for *KRAS* mutations of CRC. Receiver operating characteristics analysis revealed that the accuracy of SUVmax was highest (70%) with a cutoff value of 11, and that the TW40% method could achieve higher accuracy (71.4%) when focusing on rectal cancer. Miles *et al*[24] reported that multifunctional imaging with PET/CT and recursive decision-tree analysis to combine measurements of tumor 18F-FDG uptake (SUVmax), CT texture (expressed as mean of positive pixels) and blood perfusion (measured by dynamic contrast-enhanced CT) enabled to identify CRCs with *KRAS* mutations showing hypoxic or proliferative phenotypes. This exploratory study with 33 CRC patients indicated that the true-positive rate, false-positive rate and accuracy of the decision tree were 82.4% (63.9%-93.9%), 0% (0%-10.4%) and 90.1% (79.2%-96.0%), respectively. The accuracy of SUVmax could be improved when combined with other imaging features: SUVmax, CT texture and perfusion. Lee *et al*[25] investigated the relationship between 18F-FDG uptake-related parameters (*e.g.*, SUVmax, SUVpeak, MTV and TLG), *KRAS* mutations and C-reactive protein (CRP) with 179 CRC cases. Multivariate analysis demonstrated that SUVmax and SUVpeak are significantly associated with *KRAS* mutational status (OR, 3.3, *P* = 0.005 and OR, 3.9, *P* = 0.004, respectively) together with histological findings and lymph node metastasis. 18F-FDG accumulation was significantly higher in CRCs with mutated *KRAS* and normal CRP levels. CRCs with high CRP levels (> 6.0 mg/L; *n* = 47) was correlated to larger tumor size, higher SUVmax, higher SUVpeak, higher MTV and higher TLG, compared to those with low CRP levels (< 6.0 mg/L; *n* = 132), which indicates that local inflammation with high CRP levels could affect 18F-FDG quantification in CRC tumors.

However, the clinical benefit of above findings was limited, because endoscopic biopsy for *KRAS* mutational testing is easy in primary CRC. Importantly, we have recently examined whether a similar relationship can exist in metastatic CRC[26]. In a retrospective analysis with 55 metastatic CRC tumors, we found that SUVmax was not associated with *KRAS* mutational status. However, when focusing on tumors larger than 10mm in order to remove the partial volume effect, SUVmax was significantly higher in CRCs with mutated *KRAS* than in those with wild-type *KRAS* (8.3 ± 4.1 and 5.7 ± 2.4, respectively; *P* = 0.03). *KRAS* status of metastatic CRC was predicted with an accuracy of 71.4% when using a SUVmax cutoff value of 6.0. This is the first clinical study showing a causal relationship between 18F-FDG accumulation and *KRAS* mutations in metastatic CRC, which indicates that FDG-PET/CT scans might determine therapeutic strategies by predicting treatment response to anti-EGFR therapy. Meanwhile, Krikelis *et al*[27] reported a lack of association between 18F-FDG accumulation and *KRAS* mutational status of metastatic CRC. Although sample size and ethnic differences might be sources of the bias, we suppose that the lack of association may be due to improper patient selection. In other clinical studies, patients with high serum glucose levels, small-sized tumors or high CRP levels were excluded, because these variables interfere with 18F-FDG accumulation.

In genetically engineered mouse models (GEMM)-derived orthotopic transplant models of CRC, subcutaneous tumors from *KRAS*-mutant *APC*-/- *TP53*-/- CRC cells produced a significantly higher 18F-FDG PET signal compared to *KRAS*-wild-type APC-/- *TP53*-/- CRC cells[28]. Oncogenic *KRAS* promotes an increase in cellular glucose uptake and lactate production *in vitro* and *in vivo*.

Regarding NSCLC (*n* = 102), Caicedo *et al*[29] found that NSCLC tumors harboring *KRAS* mutations exhibited significantly higher 18F-FDG accumulation than those with wild-type *KRAS*, although no associations between different EGFR mutation types and 18F-FDG uptake were found. The sensitivity and specificity of *KRAS* mutational status were 78.6% and 62.2%, respectively, with a diagnostic accuracy of 66.7%. A multivariate model with stage, gender, age and SUVmean could predict *KRAS* mutational status in stage III or IV. A recent study using GEMM of lung cancer reported that mice harboring lung tumors with *KRAS* and *LKB1* or *TP53* mutations showed significantly higher 18F-FDG accumulation than those with only *KRAS* mutations[30]. Taken together, FDG-PET/CT scans could predict *KRAS* mutational status in a variety of human *KRAS*-related cancers (CRC, NSCLC, pancreatic cancer, *etc.*).

**HYPOXIA**

The relationship between glucose metabolism and tumor growth can be explained by adaptation to hypoxia through up-regulation of GLUTs as well as the translocation and increased enzymatic activity of HXK[31]. Hypoxia-inducible factor-1α (HIF-1α) mediates cellular response to hypoxia, such as glucose metabolism and angiogenesis. Under hypoxic conditions, HIF-1α accelerates glycolysis by up-regulation of inducing glucose transporters and some enzymes [32]. Some researchers have reported that there is a synergistic interaction between hypoxia, mutated *KRAS* and GLUT1 expression[33-36]. When CRC cells were cultured *in vitro* under hypoxia, mutated *KRAS* increased the translation of HIF-1α by the PI3K pathway[33]. In addition, hypoxia or HIF-1α could also increase mutated *KRAS* activity, which indicate that there is a positive feedback between KRAS pathway and hypoxia[36]. Hypoxia can boost expression levels of GLUT1 through HIF-1α[35]. We have recently reported that mutated *KRAS* causes higher 18F-FDG accumulation by up-regulation of GLUT1 and at least partially by induction of HIF-1α under hypoxia[37]. We also examined 51 clinical CRC samples, and found that *KRAS* mutational status was significantly associated with SUVmax and with GLUT1 expression, but not with HXK2 expression[21,35]. These data suggest that 18F-FDG accumulation observed in FDG-PET scans could reflect elevated glucose metabolism by mutated *KRAS* and hypoxia.

Goh *et al*[38] investigated the *in vivo* flow-metabolic phenotype by integrated 18F-FDG PET/perfusion CT and its relationship to histopathological findings with 45 primary CRCs. The flow-metabolic ratio was significantly lower for CRCs with high expressions of VEGF or HIF-1α compared to CRCs with lower expression, which indicated that CRCs with a low-flow-high-metabolism phenotype reflected a more angiogenic phenotype. With breast cancer cell lines, Smith *et al*[39]reported that hypoxia up-regulated GLUT1 and 6-phosphofructo-2-kinase (PFK) involved in glucose transport and glycolysis, and that these changes were induced by HIF-1α up-regulation and AMP-activated protein kinase (AMPK) activation. Preclinical studies have reported a correlation between 18F-FDG accumulation and tumor hypoxia detected by pimonidazole[40] or 18F-fluoromisonidazole (FMISO)[41], a PET tracer designed to identify hypoxic cells. Similarly, some studies noted a correlation between 18F-FDG and 18F-FMISO retention in a clinical setting [42,43].

**ONCOGENE PATHWAY ACTIVATION**

Using GEMM, Alvarez *et al*[44] investigated 18F-FDG accumulation in tumors driven by c-Myc, HER2/neu, Akt1, Wnt1 or H-RAS oncogenes, and found that 18F-FDG accumulation was correlated positively with HXK2 and HIF-1α, and negatively with PFK2b and p-AMPK. The correlation between HXK2 and 18F-FDG accumulation was not dependent on all variables tested, indicating that HXK2 could independently predict 18F-FDG accumulation in this model. In contrast, GLUT1 expression was associated with 18F-FDG accumulation only in tumors driven by Akt1 or HER2/neu. These above results demonstrated that the oncogenic pathway was a determinant of 18F-FDG accumulation mediated by glycolytic enzymes. Moreover, certain oncogenes such as Src and c-Myc, as well as elements of the PI3K/Akt pathway, can be associated with activated glycolysis[45-47].

Tian *et al*[48] investigated the correlations between SUVmax and expressions of GLUT1, hepatocyte growth factor (HGF) and vascular endothelial growth factor-C (VEGF-C) in 33 CRC patients, and found that there was a significant differences in SUVmax among CRCs expressing GLUT1, HGF, c-Met and VEGF-1. Choi *et al*[49] investigated the correlations between SUVmax and EGFR expression with 132 CRC patients, and found that SUVmax was significantly lower in EGFR-non-expressing tumors than in EGFR-expressing tumors (10.0 ± 4.2 *vs* 12.1 ± 2.1; *P* = 0.012). At the SUVmax threshold of 7.5, the sensitivity and specificity for predicting EGFR expression were 84.9% and 40.4%, which indicated SUVmax had a limited role in predicting EGFR expression. In preclinical murine models with tumor xenografts, Ma *et al.* reported that 18F-FDG PET accumulation was correlated with activated Akt and cellular membrane-bound GLUT1, and that the FDG-PET response did not correlate with the tumor growth response during mammalian target of rapamycin (mTOR) inhibitor therapy[50].

**HUMAN CYTOMEGALOVIRUS AND EPSTEIN-BARR VIRUS**

It has been debated whether human cytomegalovirus (HCMV) and Epstein-Barr virus (EBV) are involved in rectal cancer. Sole *et al*[51] reported that patients with HCMV/EBV co-infection had a significantly higher SUVmax than patients without viral co-infection, when analyzing 37 rectal cancer patients (*P* = 0.02). *KRAS* wild-type status was significantly more frequently observed in patients with EBV and HCMV/EBCV co-infection.

**F-BOX AND WD REPEAT DOMAIN-CONTAINING 7**

F-box and WD repeat domain-containing 7 (FBW7) is a E3 ubiquitin ligase and a tumor suppressor frequently mutated in CRC. In CRC, it was recently reported that FBW7 targets CDX2 (caudal-related homeobox transcription factor 2) for degradation *via* two cdc42-phosphoclegron motifs in a GSK3beta-dependent manner[52]. Ji *et al*[53] have recently reported that *KRAS* mutations inhibit the tumor suppressor FBW7, which negatively regulates glucose metabolism by targeting the c-Myc/TXNIP (thioredoxin binding protein) axis in pancreatic cancer. The expression level of FBW7 was negatively associated with PET/CT SUVmax in 60 pancreatic cancer patients, indicating that FBW7 is an important KRAS downstream effector and might reverse KRAS-driven metabolic change.

**LACTATE DEHYDROGENASE A**

Lactate dehydrogenase A (LDHA) converts pyruvate to lactate and is overexpressed in many cancers[54]. Up-regulation of LDHA ensures efficient glycolytic metabolism for tumor cells and reduces oxygen dependency[55]. In a retrospective analysis of 51 lung adenocarcinomas, Zhou *et al*[56] reported that SUVmax was significantly higher in the LDHA high-expression group than the LDHA low-expression group (*P* = 0.018). GLUT1 expression in lung adenocarcinomas was significantly associated with 18F-FDG accumulation and LDHA expression, whereas HXK2 expression was not. In CRC, it was recently reported that LDHA negatively regulated by miRNAs promotes aerobic glycolysis[57].

**PROLIFERATION-ASSOCIATED ANTIGEN KI-67**

According to a meta-analysis (81 studies, 3242 patients), Deng *et al*[58]reported that the relationship between 18F-FDG accumulation and Ki-67 expression was significant in thymic epithelial tumors, gastrointestinal stromal tumors (GISTs), moderate in breast, lung and pancreatic cancers, and average in CRCs, and poor in thyroid and gastric cancers.

**CONCLUSION**

For prediction of *KRAS* mutations in CRC, the overall accuracy of SUVmax alone has only been found to be modest, ranging from 60% to 75%, although the accuracy could be improved when combined with other clinicopathologic or imaging parameters. New targeted therapies are being developed for tumors that selectively express *KRAS* mutations[59]. Hence, the availability of non-invasive methods, such as molecular imaging, for predicting *KRAS* mutational status could have considerable clinical relevance, because of their potential to improve the assessment of other molecular alterations in the future. Future advances in PET radiotracers may increase the sensitivity and specificity of this technique to provide full molecular assessment of CRC.

# REFERENCES

1. **de Geus-Oei LF**, Vriens D, van Laarhoven HW, van der Graaf WT, Oyen WJ. Monitoring and predicting response to therapy with 18F-FDG PET in colorectal cancer: a systematic review. *J Nucl Med* 2009; **50** Suppl 1: 43S-54S [PMID: 19403879 DOI: 10.2967/jnumed.108.057224]
2. **Moulton CA**, Gu CS, Law CH, Tandan VR, Hart R, Quan D, Fairfull Smith RJ, Jalink DW, Husien M, Serrano PE, Hendler AL, Haider MA, Ruo L, Gulenchyn KY, Finch T, Julian JA, Levine MN, Gallinger S. Effect of PET before liver resection on surgical management for colorectal adenocarcinoma metastases: a randomized clinical trial. *JAMA* 2014; **311**: 1863-1869 [PMID: 24825641 DOI: 10.1001/jama.2014.3740]
3. **Warburg O**. On the origin of cancer cells. *Science* 1956; **123**: 309-314 [PMID: 13298683 DOI: 10.1126/science.123.3191.309]
4. **Koppenol WH**, Bounds PL, Dang CV. Otto Warburg's contributions to current concepts of cancer metabolism. *Nat Rev Cancer* 2011; **11**: 325-337 [PMID: 21508971 DOI: 10.1038/nrc3038]
5. **Pauwels EK**, Ribeiro MJ, Stoot JH, McCready VR, Bourguignon M, Mazière B. FDG accumulation and tumor biology. *Nucl Med Biol* 1998; **25**: 317-322 [PMID: 9639291 DOI: 10.1016/S0969-8051(97)00226-6]
6. **Gillies RJ**, Robey I, Gatenby RA. Causes and consequences of increased glucose metabolism of cancers. *J Nucl Med* 2008; **49** Suppl 2: 24S-42S [PMID: 18523064 DOI: 10.2967/jnumed.107.047258]
7. **Plathow C**, Weber WA. Tumor cell metabolism imaging. *J Nucl Med* 2008; **49 Suppl 2**: 43S-63S [PMID: 18523065 DOI: 10.2967/jnumed.107.045930]
8. **Weitz J**, Koch M, Debus J, Höhler T, Galle PR, Büchler MW. Colorectal cancer. *Lancet* 2005; **365**: 153-165 [PMID: 15639298 DOI: 10.1016/S0140-6736(05)17706-X]
9. **Weinberg RA**. Multi-step tumorigenesis. In: The biology of cancer. Chapter 11. New York, NY: Garland Science Taylor & Francis Group, LLC, 2007; **11**: 399-462
10. **Jadvar H**, Alavi A, Gambhir SS. 18F-FDG uptake in lung, breast, and colon cancers: molecular biology correlates and disease characterization. *J Nucl Med* 2009; **50**: 1820-1827 [PMID: 19837767 DOI: 10.2967/jnumed.108.054098]
11. **Medina RA**, Owen GI. Glucose transporters: expression, regulation and cancer. *Biol Res* 2002; **35**: 9-26 [PMID: 12125211 DOI: 10.4067/S0716-97602002000100004]
12. **Smith TA**. Facilitative glucose transporter expression in human cancer tissue. *Br J Biomed Sci* 1999; **56**: 285-292 [PMID: 10795374]
13. **Mathupala SP**, Ko YH, Pedersen PL. Hexokinase II: cancer's double-edged sword acting as both facilitator and gatekeeper of malignancy when bound to mitochondria. *Oncogene* 2006; **25**: 4777-4786 [PMID: 16892090 DOI: 10.1038/sj.onc.1209603]
14. **Smith TA**. Mammalian hexokinases and their abnormal expression in cancer. *Br J Biomed Sci* 2000; **57**: 170-178 [PMID: 10912295]
15. **Maddalena F**, Lettini G, Gallicchio R, Sisinni L, Simeon V, Nardelli A, Venetucci AA, Storto G, Landriscina M. Evaluation of Glucose Uptake in Normal and Cancer Cell Lines by Positron Emission Tomography. *Mol Imaging* 2015; **14**: 490-498 [PMID: 26461458]
16. **Jonker DJ**, O'Callaghan CJ, Karapetis CS, Zalcberg JR, Tu D, Au HJ, Berry SR, Krahn M, Price T, Simes RJ, Tebbutt NC, van Hazel G, Wierzbicki R, Langer C, Moore MJ. Cetuximab for the treatment of colorectal cancer. *N Engl J Med* 2007; **357**: 2040-2048 [PMID: 18003960 DOI: 10.1056/NEJMoa071834]
17. **Karapetis CS**, Khambata-Ford S, Jonker DJ, O'Callaghan CJ, Tu D, Tebbutt NC, Simes RJ, Chalchal H, Shapiro JD, Robitaille S, Price TJ, Shepherd L, Au HJ, Langer C, Moore MJ, Zalcberg JR. K-ras mutations and benefit from cetuximab in advanced colorectal cancer. *N Engl J Med* 2008; **359**: 1757-1765 [PMID: 18946061 DOI: 10.1056/NEJMoa0804385]
18. **Baldus SE**, Schaefer KL, Engers R, Hartleb D, Stoecklein NH, Gabbert HE. Prevalence and heterogeneity of KRAS, BRAF, and PIK3CA mutations in primary colorectal adenocarcinomas and their corresponding metastases. *Clin Cancer Res* 2010; **16**: 790-799 [PMID: 20103678 DOI: 10.1158/1078-0432.CCR-09-2446]
19. **Albanese I**, Scibetta AG, Migliavacca M, Russo A, Bazan V, Tomasino RM, Colomba P, Tagliavia M, La Farina M. Heterogeneity within and between primary colorectal carcinomas and matched metastases as revealed by analysis of Ki-ras and p53 mutations. *Biochem Biophys Res Commun* 2004; **325**: 784-791 [PMID: 15541358 DOI: 10.1016/j.bbrc.2004.10.111]
20. **Molinari F**, Martin V, Saletti P, De Dosso S, Spitale A, Camponovo A, Bordoni A, Crippa S, Mazzucchelli L, Frattini M. Differing deregulation of EGFR and downstream proteins in primary colorectal cancer and related metastatic sites may be clinically relevant. *Br J Cancer* 2009; **100**: 1087-1094 [PMID: 19293803 DOI: 10.1038/sj.bjc.6604848]
21. **Yun J**, Rago C, Cheong I, Pagliarini R, Angenendt P, Rajagopalan H, Schmidt K, Willson JK, Markowitz S, Zhou S, Diaz LA, Velculescu VE, Lengauer C, Kinzler KW, Vogelstein B, Papadopoulos N. Glucose deprivation contributes to the development of KRAS pathway mutations in tumor cells. *Science* 2009; **325**: 1555-1559 [PMID: 19661383 DOI: 10.1126/science.1174229]
22. **Kawada K**, Nakamoto Y, Kawada M, Hida K, Matsumoto T, Murakami T, Hasegawa S, Togashi K, Sakai Y. Relationship between 18F-fluorodeoxyglucose accumulation and KRAS/BRAF mutations in colorectal cancer. *Clin Cancer Res* 2012; **18**: 1696-1703 [PMID: 22282467 DOI: 10.1158/1078-0432.CCR-11-1909]
23. **Chen SW**, Chiang HC, Chen WT, Hsieh TC, Yen KY, Chiang SF, Kao CH. Correlation between PET/CT parameters and KRAS expression in colorectal cancer. *Clin Nucl Med* 2014; **39**: 685-689 [PMID: 24978328 DOI: 10.1097/RLU.0000000000000481]
24. **Miles KA**, Ganeshan B, Rodriguez-Justo M, Goh VJ, Ziauddin Z, Engledow A, Meagher M, Endozo R, Taylor SA, Halligan S, Ell PJ, Groves AM. Multifunctional imaging signature for V-KI-RAS2 Kirsten rat sarcoma viral oncogene homolog (KRAS) mutations in colorectal cancer. *J Nucl Med* 2014; **55**: 386-391 [PMID: 24516257 DOI: 10.2967/jnumed.113.120485]
25. **Lee JH**, Kang J, Baik SH, Lee KY, Lim BJ, Jeon TJ, Ryu YH, Sohn SK. Relationship Between 18F-Fluorodeoxyglucose Uptake and V-Ki-Ras2 Kirsten Rat Sarcoma Viral Oncogene Homolog Mutation in Colorectal Cancer Patients: Variability Depending on C-Reactive Protein Level. *Medicine (Baltimore)* 2016; **95**: e2236 [PMID: 26735530 DOI: 10.1097/MD.0000000000002236]
26. **Kawada K**, Toda K, Nakamoto Y, Iwamoto M, Hatano E, Chen F, Hasegawa S, Togashi K, Date H, Uemoto S, Sakai Y. Relationship Between 18F-FDG PET/CT Scans and KRAS Mutations in Metastatic Colorectal Cancer. *J Nucl Med* 2015; **56**: 1322-1327 [PMID: 26135109 DOI: 10.2967/jnumed.115.160614]
27. **Krikelis D**, Skoura E, Kotoula V, Rondogianni P, Pianou N, Samartzis A, Xanthakis I, Fountzilas G, Datseris IE. Lack of association between KRAS mutations and 18F-FDG PET/CT in Caucasian metastatic colorectal cancer patients. *Anticancer Res* 2014; **34**: 2571-2579 [PMID: 24778079]
28. **Martin ES**, Belmont PJ, Sinnamon MJ, Richard LG, Yuan J, Coffee EM, Roper J, Lee L, Heidari P, Lunt SY, Goel G, Ji X, Xie Z, Xie T, Lamb J, Weinrich SL, VanArsdale T, Bronson RT, Xavier RJ, Vander Heiden MG, Kan JL, Mahmood U, Hung KE. Development of a colon cancer GEMM-derived orthotopic transplant model for drug discovery and validation. *Clin Cancer Res* 2013; **19**: 2929-2940 [PMID: 23403635 DOI: 10.1158/1078-0432.CCR-12-2307]
29. **Caicedo C**, Garcia-Velloso MJ, Lozano MD, Labiano T, Vigil Diaz C, Lopez-Picazo JM, Gurpide A, Zulueta JJ, Richter Echevarria JA, Perez Gracia JL. Role of [¹⁸F]FDG PET in prediction of KRAS and EGFR mutation status in patients with advanced non-small-cell lung cancer. *Eur J Nucl Med Mol Imaging* 2014; **41**: 2058-2065 [PMID: 24990403 DOI: 10.1007/s00259-014-2833-4]
30. **Chen Z**, Cheng K, Walton Z, Wang Y, Ebi H, Shimamura T, Liu Y, Tupper T, Ouyang J, Li J, Gao P, Woo MS, Xu C, Yanagita M, Altabef A, Wang S, Lee C, Nakada Y, Peña CG, Sun Y, Franchetti Y, Yao C, Saur A, Cameron MD, Nishino M, Hayes DN, Wilkerson MD, Roberts PJ, Lee CB, Bardeesy N, Butaney M, Chirieac LR, Costa DB, Jackman D, Sharpless NE, Castrillon DH, Demetri GD, Jänne PA, Pandolfi PP, Cantley LC, Kung AL, Engelman JA, Wong KK. A murine lung cancer co-clinical trial identifies genetic modifiers of therapeutic response. *Nature* 2012; **483**: 613-617 [PMID: 22425996 DOI: 10.1038/nature10937]
31. **Macheda ML**, Rogers S, Best JD. Molecular and cellular regulation of glucose transporter (GLUT) proteins in cancer. *J Cell Physiol* 2005; **202**: 654-662 [PMID: 15389572 DOI: 10.1002/jcp.20166]
32. **Semenza GL**. HIF-1 mediates metabolic responses to intratumoral hypoxia and oncogenic mutations. *J Clin Invest* 2013; **123**: 3664-3671 [PMID: 23999440 DOI: 10.1172/JCI67230]
33. **Kikuchi H**, Pino MS, Zeng M, Shirasawa S, Chung DC. Oncogenic KRAS and BRAF differentially regulate hypoxia-inducible factor-1alpha and -2alpha in colon cancer. *Cancer Res* 2009; **69**: 8499-8506 [PMID: 19843849 DOI: 10.1158/0008-5472.CAN-09-2213]
34. **Zeng M**, Kikuchi H, Pino MS, Chung DC. Hypoxia activates the K-ras proto-oncogene to stimulate angiogenesis and inhibit apoptosis in colon cancer cells. *PLoS One* 2010; **5**: e10966 [PMID: 20532039 DOI: 10.1371/journal.pone.0010966]
35. **Lee-Kong SA**, Ruby JA, Chessin DB, Pucciarelli S, Shia J, Riedel ER, Nitti D, Guillem JG. Hypoxia-related proteins in patients with rectal cancer undergoing neoadjuvant combined modality therapy. *Dis Colon Rectum* 2012; **55**: 990-995 [PMID: 22874607 DOI: 10.1097/DCR.0b013e31825bd80c]
36. **Wang Y**, Lei F, Rong W, Zeng Q, Sun W. Positive feedback between oncogenic KRAS and HIF-1α confers drug resistance in colorectal cancer. *Onco Targets Ther* 2015; **8**: 1229-1237 [PMID: 26060408 DOI: 10.2147/OTT.S80017]
37. **Iwamoto M**, Kawada K, Nakamoto Y, Itatani Y, Inamoto S, Toda K, Kimura H, Sasazuki T, Shirasawa S, Okuyama H, Inoue M, Hasegawa S, Togashi K, Sakai Y. Regulation of 18F-FDG accumulation in colorectal cancer cells with mutated KRAS. *J Nucl Med* 2014; **55**: 2038-2044 [PMID: 25453050 DOI: 10.2967/jnumed.114.142927]
38. **Goh V**, Engledow A, Rodriguez-Justo M, Shastry M, Peck J, Blackman G, Endozo R, Taylor S, Halligan S, Ell P, Groves AM. The flow-metabolic phenotype of primary colorectal cancer: assessment by integrated 18F-FDG PET/perfusion CT with histopathologic correlation. *J Nucl Med* 2012; **53**: 687-692 [PMID: 22454485 DOI: 10.2967/jnumed.111.098525]
39. **Smith TA**, Zanda M, Fleming IN. Hypoxia stimulates 18F-fluorodeoxyglucose uptake in breast cancer cells via hypoxia inducible factor-1 and AMP-activated protein kinase. *Nucl Med Biol* 2013; **40**: 858-864 [PMID: 23786679 DOI: 10.1016/j.nucmedbio.2013.05.006]
40. **Dearling JL**, Flynn AA, Sutcliffe-Goulden J, Petrie IA, Boden R, Green AJ, Boxer GM, Begent RH, Pedley RB. Analysis of the regional uptake of radiolabeled deoxyglucose analogs in human tumor xenografts. *J Nucl Med* 2004; **45**: 101-107 [PMID: 14734681]
41. **Wyss MT**, Honer M, Schubiger PA, Ametamey SM. NanoPET imaging of [(18)F]fluoromisonidazole uptake in experimental mouse tumours. *Eur J Nucl Med Mol Imaging* 2006; **33**: 311-318 [PMID: 16258762 DOI: 10.1007/s00259-005-1951-4]
42. **Rajendran JG**, Mankoff DA, O'Sullivan F, Peterson LM, Schwartz DL, Conrad EU, Spence AM, Muzi M, Farwell DG, Krohn KA. Hypoxia and glucose metabolism in malignant tumors: evaluation by [18F]fluoromisonidazole and [18F]fluorodeoxyglucose positron emission tomography imaging. *Clin Cancer Res* 2004; **10**: 2245-2252 [PMID: 15073099 DOI: 10.1158/1078-0432.CCR-0688-3]
43. **Zimny M**, Gagel B, DiMartino E, Hamacher K, Coenen HH, Westhofen M, Eble M, Buell U, Reinartz P. FDG--a marker of tumour hypoxia? A comparison with [18F]fluoromisonidazole and pO2-polarography in metastatic head and neck cancer. *Eur J Nucl Med Mol Imaging* 2006; **33**: 1426-1431 [PMID: 16841141 DOI: 10.1007/s00259-006-0175-6]
44. **Alvarez JV**, Belka GK, Pan TC, Chen CC, Blankemeyer E, Alavi A, Karp JS, Chodosh LA. Oncogene pathway activation in mammary tumors dictates FDG-PET uptake. *Cancer Res* 2014; **74**: 7583-7598 [PMID: 25239452 DOI: 10.1158/0008-5472.CAN-14-1235]
45. **Flier JS**, Mueckler MM, Usher P, Lodish HF. Elevated levels of glucose transport and transporter messenger RNA are induced by ras or src oncogenes. *Science* 1987; **235**: 1492-1495 [PMID: 3103217 DOI: 10.1126/science.3103217]
46. **Osthus RC**, Shim H, Kim S, Li Q, Reddy R, Mukherjee M, Xu Y, Wonsey D, Lee LA, Dang CV. Deregulation of glucose transporter 1 and glycolytic gene expression by c-Myc. *J Biol Chem* 2000; **275**: 21797-21800 [PMID: 10823814 DOI: 10.1074/jbc.C000023200]
47. **Wieman HL**, Wofford JA, Rathmell JC. Cytokine stimulation promotes glucose uptake via phosphatidylinositol-3 kinase/Akt regulation of Glut1 activity and trafficking. *Mol Biol Cell* 2007; **18**: 1437-1446 [PMID: 17301289 DOI: 10.1091/mbc.E06-07-0593]
48. **Tian M**, Yu L, Zhang Y, Gao X. Correlations between SUVmax and expression of GLUT1 and growth factors inducing lymphangiogenesis. *Acad Radiol* 2012; **19**: 420-426 [PMID: 22444673 DOI: 10.1016/j.acra.2011.12.006]
49. **Choi YJ**, Kim MJ, Lee BH, Kwon MJ, Hwang HS. Relationship between Preoperative ¹⁸F-Fluorodeoxyglucose Uptake and Epidermal Growth Factor Receptor Status in Primary Colorectal Cancer. *Yonsei Med J* 2016; **57**: 232-237 [PMID: 26632406 DOI: 10.3349/ymj.2016.57.1.232]
50. **Ma WW**, Jacene H, Song D, Vilardell F, Messersmith WA, Laheru D, Wahl R, Endres C, Jimeno A, Pomper MG, Hidalgo M. [18F]fluorodeoxyglucose positron emission tomography correlates with Akt pathway activity but is not predictive of clinical outcome during mTOR inhibitor therapy. *J Clin Oncol* 2009; **27**: 2697-2704 [PMID: 19380450 DOI: 10.1200/JCO.2008.18.8383]
51. **Sole CV**, Calvo FA, Ferrer C, Alvarez E, Carreras JL, Ochoa E. Human cytomegalovirus and Epstein-Barr virus infection impact on (18)F-FDG PET/CT SUVmax, CT volumetric and KRAS-based parameters of patients with locally advanced rectal cancer treated with neoadjuvant therapy. *Eur J Nucl Med Mol Imaging* 2015; **42**: 186-196 [PMID: 25269837 DOI: 10.1007/s00259-014-2910-8]
52. [**Kumar Y**](http://www.ncbi.nlm.nih.gov/pubmed/?term=Kumar%20Y%5BAuthor%5D&cauthor=true&cauthor_uid=27470268), [Shukla N](http://www.ncbi.nlm.nih.gov/pubmed/?term=Shukla%20N%5BAuthor%5D&cauthor=true&cauthor_uid=27470268), [Thacker G](http://www.ncbi.nlm.nih.gov/pubmed/?term=Thacker%20G%5BAuthor%5D&cauthor=true&cauthor_uid=27470268), [Kapoor I](http://www.ncbi.nlm.nih.gov/pubmed/?term=Kapoor%20I%5BAuthor%5D&cauthor=true&cauthor_uid=27470268), [Lochab S](http://www.ncbi.nlm.nih.gov/pubmed/?term=Lochab%20S%5BAuthor%5D&cauthor=true&cauthor_uid=27470268), [Bhatt ML](http://www.ncbi.nlm.nih.gov/pubmed/?term=Bhatt%20ML%5BAuthor%5D&cauthor=true&cauthor_uid=27470268), [Chattopadhyay N](http://www.ncbi.nlm.nih.gov/pubmed/?term=Chattopadhyay%20N%5BAuthor%5D&cauthor=true&cauthor_uid=27470268), [Sanyal S](http://www.ncbi.nlm.nih.gov/pubmed/?term=Sanyal%20S%5BAuthor%5D&cauthor=true&cauthor_uid=27470268), [Trivedi AK](http://www.ncbi.nlm.nih.gov/pubmed/?term=Trivedi%20AK%5BAuthor%5D&cauthor=true&cauthor_uid=27470268). Ubiquitin Ligase, Fbw7, Targets CDX2 for Degradation via Two Phosphodegron Motifs in a GSK3beta-dependent Manner. *Mol Cancer Res* 2016 Jul 28; Epub ahead of print [PMID: [27470268](http://www.ncbi.nlm.nih.gov/pubmed/27470268) DOI: [10.1158/1541-7786.MCR-16-0138](http://dx.doi.org/10.1158/1541-7786.MCR-16-0138)]
53. **Ji S**, Qin Y, Liang C, Huang R, Shi S, Liu J, Jin K, Liang D, Xu W, Zhang B, Liu L, Liu C, Xu J, Ni Q, Chiao PJ, Li M, Yu X. FBW7 (F-box and WD Repeat Domain-Containing 7) Negatively Regulates Glucose Metabolism by Targeting the c-Myc/TXNIP (Thioredoxin-Binding Protein) Axis in Pancreatic Cancer. *Clin Cancer Res* 2016; **22**: 3950-3960 [PMID: 26983463 DOI: 10.1158/1078-0432.CCR-15-2380]
54. **Miao P**, Sheng S, Sun X, Liu J, Huang G. Lactate dehydrogenase A in cancer: a promising target for diagnosis and therapy. *IUBMB Life* 2013; **65**: 904-910 [PMID: 24265197 DOI: 10.1002/iub.1216]
55. **Fantin VR**, St-Pierre J, Leder P. Attenuation of LDH-A expression uncovers a link between glycolysis, mitochondrial physiology, and tumor maintenance. *Cancer Cell* 2006; **9**: 425-434 [PMID: 16766262 DOI: 10.1016/j.ccr.2006.04.023]
56. **Zhou X**, Chen R, Xie W, Ni Y, Liu J, Huang G. Relationship between 18F-FDG accumulation and lactate dehydrogenase A expression in lung adenocarcinomas. *J Nucl Med* 2014; **55**: 1766-1771 [PMID: 25342384 DOI: 10.2967/jnumed.114.145490]
57. **Wang J**, Wang H, Liu A, Fang C, Hao J, Wang Z. Lactate dehydrogenase A negatively regulated by miRNAs promotes aerobic glycolysis and is increased in colorectal cancer. *Oncotarget* 2015; **6**: 19456-19468 [PMID: 26062441 DOI: 10.18632/oncotarget.3318]
58. **Deng SM**, Zhang W, Zhang B, Chen YY, Li JH, Wu YW. Correlation between the Uptake of 18F-Fluorodeoxyglucose (18F-FDG) and the Expression of Proliferation-Associated Antigen Ki-67 in Cancer Patients: A Meta-Analysis. *PLoS One* 2015; **10**: e0129028 [PMID: 26038827 DOI: 10.1371/journal.pone.0129028]
59. **Ostrem JM**, Peters U, Sos ML, Wells JA, Shokat KM. K-Ras(G12C) inhibitors allosterically control GTP affinity and effector interactions. *Nature* 2013; **503**: 548-551 [PMID: 24256730 DOI: 10.1038/nature12796]

**P-Reviewer:** Chen K, Palumbo B **S-Editor:** Kong JX **L-Editor: E-Editor:**

**Table 1 Clinical reports investigating the relationship between 18F-fluorodeoxyglucose accumulation and *KRAS* mutations**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Ref.** | **Cancer type** | | **Sample size** | **Parameters related to *KRAS* mutations** | **Sensitivity (%)** | **Specificity**  **(%)** | **Accuracy (%)** |
| Kawada *et al*[21] | CRC | 51 | | SUVmax | 74 | 75 | 75 |
| TLR | 70 | 71 | 71 |
| Chen *et al*[22] | CRC | 121 | | SUVmax | 52.4 | 71.7 | 70 |
|  | CRC | 121 | | TW40% | 53.2 | 67.6 | 62 |
|  | RC | 49 | | TW40% | 80 | 79.1 | 71.4 |
| Miles *et al*[23] | CRC | 33 | | Dicision tree with SUVmax, MPP and BF | 82.4 | 100 | 90.1 |
| Lee *et al*[24] | CRC | 132 | | SUVmax | 60 | 50.3 | 54 |
|  |  |  | | SUVpeak | 73.3 | 60.5 | 67.8 |
| Caicedo *et al*[28] | NSCLC | 102 | | SUVmean | 78.6 | 62.2 | 66.7 |
| Kawada *et al*[25] | mCRC | 42 | | SUVmax | 68 | 74 | 71.4 |

SUV: Standardized uptake value; TLR: Tumor-to-liver SUV ratio; TW40%: A 40% threshold level of SUVmax for tumor width; MPP: Mean of positive pixels; BF: Blood flow; CRC: Colorectal cancer; RC: Rectal cancer; NSCLC: Non-small-cell lung cancer; mCRC: Metastatic CRC.