



Current management of succinate dehydrogenase–deficient gastrointestinal stromal tumors

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Abstract

Gastrointestinal stromal tumors (GISTs) are increasingly recognized as having diverse biology. With the development of tyrosine kinase inhibitors molecularly matched to oncogenic *KIT* and *PDGFRA* mutations, GISTs have become a quintessential model for precision oncology. However, about 5–10% of GIST lack these driver mutations and are deficient in succinate dehydrogenase (SDH), an enzyme that converts succinate to fumarate. SDH deficiency leads to accumulation of succinate, an oncometabolite that promotes tumorigenesis. SDH-deficient GISTs are clinically unique in that they generally affect younger patients and are associated with GIST-paraganglioma hereditary syndrome, also known as Carney-Stratakis Syndrome. SDH-deficient GISTs are generally resistant to tyrosine-kinase inhibitors, the standard treatment for advanced or metastatic GIST. Thus, surgical resection is the mainstay of treatment for localized disease, but recurrence is common. Clinical trials are currently underway investigating systemic agents for treatment of advanced SDH-deficient GIST. However, further studies are warranted to improve our understanding of SDH-deficient GIST disease biology, natural history, surgical approaches, and novel therapeutics.

Keywords: Gastrointestinal stromal tumors · GIST · Succinate dehydrogenase · Tyrosine kinase inhibitors · SDH

1 Introduction

Gastrointestinal stromal tumors (GISTs) are the most common sarcoma, affecting 6.8 per million people

annually in the USA [1]. GISTs arise from interstitial cells of Cajal, which are pacemaker cells in the gut that control the slow wave of smooth muscle contraction [2]. GIST can arise anywhere in the gastrointestinal tract but occur most often in the stomach and small bowel [3–5]. They also can have histopathologic heterogeneity ranging from spindleoid to epithelioid to mixed histologies [6–8]. Moreover, GISTs are driven by a variety of oncogenic driver or loss of function mutations, making them molecularly diverse [3, 4].

Before the advent of targeted cancer therapies, the prognosis for GIST was poor given their resistance to conventional chemotherapy and radiation [9]. In 1998, gain-of-function mutations in *KIT* were identified. These mutations activate the receptor tyrosine kinase c-KIT via ligand-independent receptor dimerization, which promotes downstream signaling. This leads to unchecked tumor cell growth and survival [10]. We now know that 70–80% of GIST have mutations in *KIT* or another receptor tyrosine kinase, *PDGFRA* [11, 12]. Tyrosine kinase inhibitors such as imatinib target mutations in *KIT* and *PDGFRA* and are the mainstay of treatment. Therefore, GISTs have become an important proof-of-

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principle model for precision therapy in cancer patients [9, 13].

Further studies of the molecular biology of GIST have identified additional GIST subsets caused by mutations of *K/H/N-RAS*, *BRAF*, and *NF1*, as well as gene fusions of *FGFR1* and *ETV6-NTRK3* [12, 14–17]. Additionally, another 5–10% of GIST has mutations in succinate dehydrogenase (SDH) subunits [18, 19]. Mutations in SDH subunits have been linked to a number of cancers. More importantly, they were first linked to GIST in the setting of hereditary GIST-paraganglioma syndrome, also known as Carney-Stratakis Syndrome [20].

2 Clinical and pathologic features of SDH-deficient GIST

The median age of diagnosis of GIST is 64 years old, but SDH-deficient GIST usually first appear in children, adolescents, and young adults [1]. However, patients in their 40s to late 50s also can present with an initial diagnosis of SDH-deficient GIST (Sicklick, unpublished data). Over 80% of pediatric GIST has inactivating mutations in SDH subunits [20–22]. Females are reported to be disproportionately affected [18]. However, in our practice of young adults with GIST, we have observed a higher proportion of male patients with SDH mutations (Fanta, Burgoyne, and Sicklick, unpublished data).

SDH-deficient GISTs generally arise in the stomach. The clinical presentation is often non-specific, which leads to a delay in diagnosis. Many patients with GIST are diagnosed after presenting with severe epigastric pain or gastrointestinal bleeding due to ulceration [19, 23]. This is consistent with the indolent biology of these tumors. In fact, often patients present with gastric recurrences and lymph node metastases later in life, a phenomenon that is less common in SDH-competent GIST. Recurrence often leads to repeat partial gastrectomy [19, 24]. Histology often shows epithelial hypercellularity and lymphovascular invasion, as well as multifocality, which is also rarer in *KIT/PDGFR*A-mutated GIST. Thus, the natural history and biology of these SDH-deficient tumors are distinct from their oncogene-driven counterparts.

3 Structure and function of the SDH complex

The SDH complex is a component of complex II in the Krebs cycle, a process that connects glycolysis in the cytoplasm to oxidative phosphorylation in the mitochondria (Fig. 1). This complex resides in the inner mitochondrial membrane and has four subunits, encoded by the *SDHA*, *SDHB*, *SDHC*, and *SDHD* genes. In mammalian mitochondria, SDHA forms the catalytic core, while SDHB forms an iron-sulfur protein, and SDHC/SDHD are integral membrane proteins (Fig. 2) [25, 26].

Although SDH is an essential part of normal cellular metabolism, SDH-deficient cancer cells continue to proliferate, suggesting that metabolic variability must exist in these cells. Bioinformatic analysis of SDH mutated pheochromocytomas and paragangliomas (PPGLs) revealed that these cells become highly dependent on aspartate through increased pyruvate carboxylation [27]. In fact, deficiency of SDHB has been shown to lead to a complete block of the Krebs cycle, with cells consuming extracellular pyruvate and deriving most energy needs through glycolysis alone. In these cells, pyruvate carboxylase activity is crucial for continued growth [28].

4 SDH loss in tumorigenesis

The SDH complex is involved in the conversion of succinate to fumarate during cellular respiration. Tumors with inactivating mutations in *SDHx* genes lack a functional SDH complex, losing the ability to convert succinate to fumarate. Thus, they are considered to be SDH-deficient. In 1977, SDH deficiency was first described in a mutant Chinese hamster fibroblast cell line [29]. Lack of SDH in this system resulted in a defect of oxidative phosphorylation, as well increased cellular reliance on glycolysis for energy metabolism. *SDHx* mutations were first linked to cancer in 2000 when germline mutations in *SDHD* were reported in hereditary paraganglioma [30]. Since that time, *SDHx* mutations have been implicated in a number of tumor types including carcinomas (i.e., renal cell, thyroid) and other neuroendocrine tumors (i.e., neuroblastoma, paraganglioma, pheochromocytoma) [31–34], as well as GIST.

Mutations in *SDHx* result in an accumulation of succinate. Similarly, deficiency of fumarate hydratase (FH) results in an accumulation of fumarate. Both succinate and fumarate have been implicated as oncometabolites, a term used to describe how these metabolites dysregulate oxygen-dependent signaling in the tumor microenvironment [35–37]. Under normoxic conditions, hypoxia-inducible factor 1 α (HIF1 α) is hydroxylated by prolyl hydroxylase domain (PHD) proteins, via an oxygen-dependent reaction that converts α -ketoglutarate (α -KG) to succinate, which in turn targets HIF1 α for proteasome-mediated degradation. In hypoxic conditions such as those within a tumor environment, HIF1 α accumulates and translocates into the nucleus where it complexes with HIF1 β to promote the transcription of genes involved in angiogenesis, proliferation, and glycolysis [38]. However, deficiency of either SDH or FH leads to the accumulation of succinate or fumarate, respectively, inhibiting PHDs and leading to the stabilization and accumulation of HIF1 α in normoxic conditions [37, 39]. Such HIF1 α activation under normoxic conditions is termed pseudohypoxia. In this setting, HIF1 α activation supports increased angiogenesis and glycolysis, processes that enhance tumor growth. Furthermore, the exogenous administration of α -KG allows PHDs to overcome inhibition by succinate in

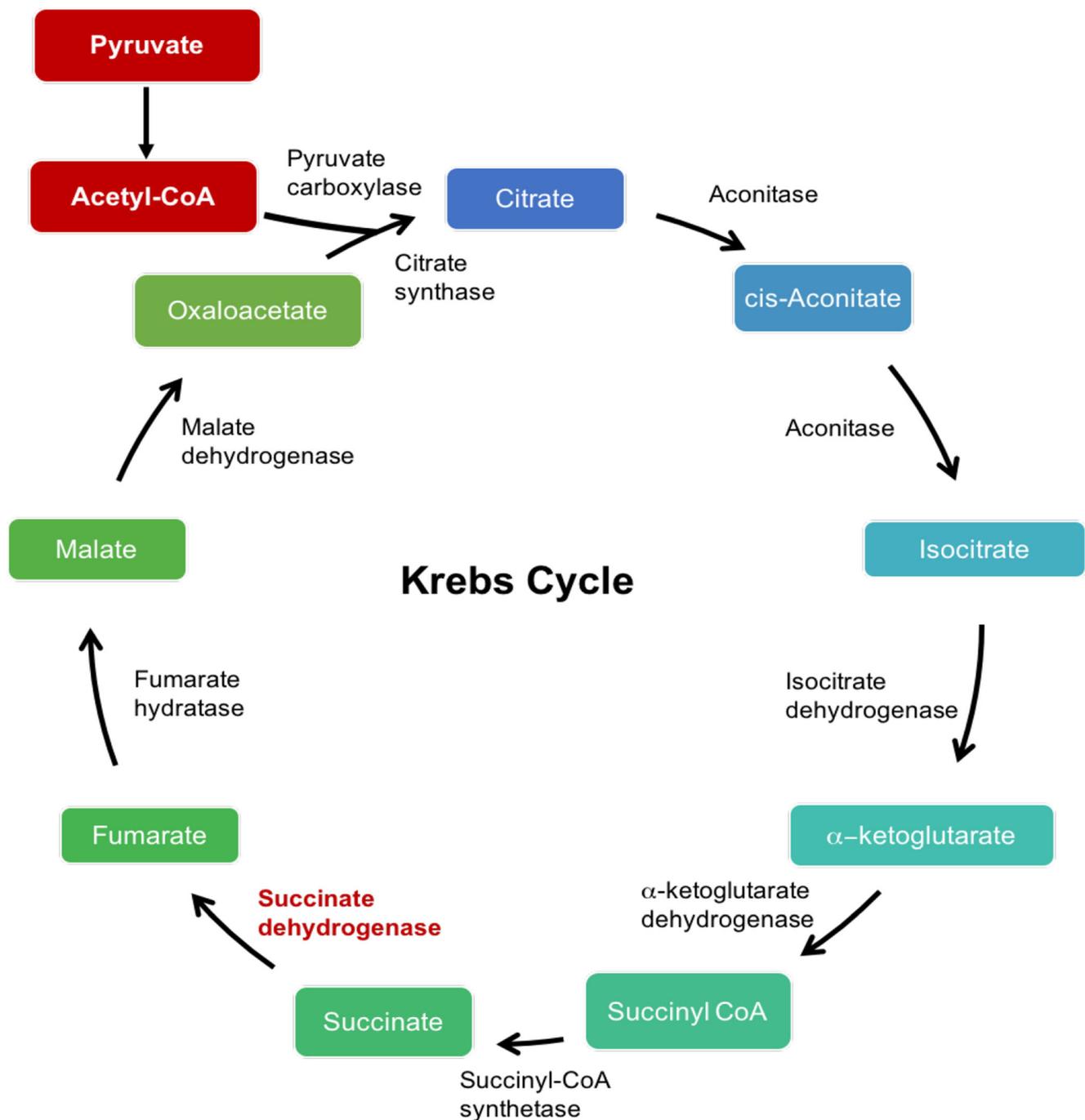


Fig. 1 Schematic of the Krebs cycle. The succinate dehydrogenase (SDH) complex converts succinate to fumarate

SDH-deficient tumor cells through a concentration-dependent manner [40]. This suggests α -KG may be a potential therapeutic target in SDH-deficient GIST.

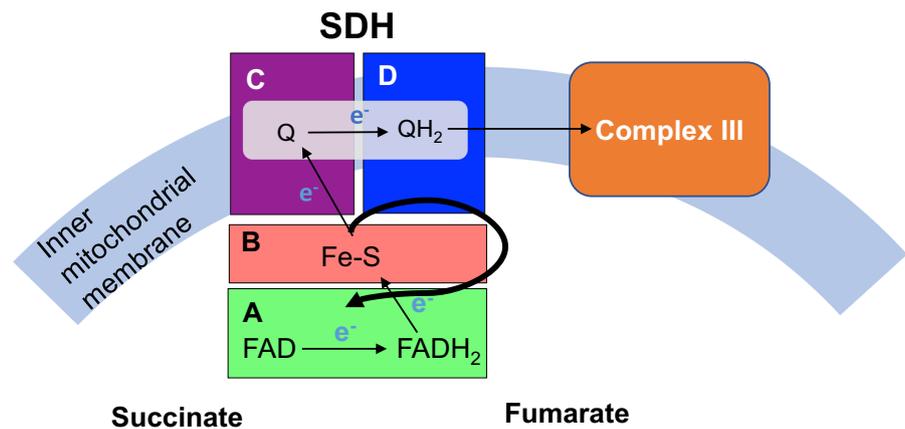
5 SDH loss in metastasis

Epithelial-to-mesenchymal transition (EMT) describes the process of epithelial cancer cells taking on mesenchymal

features. EMT is important for embryonic development and wound healing, but in the setting of tumor biology, it leads to the invasion of cancer cells and eventual metastasis. Over the last decade, there has been emerging knowledge regarding the role of Krebs cycle enzymes and mitochondrial dysfunction in EMT [41].

SDH was first implicated in increased EMT in mouse cancer ovarian cells. Knockdown of *SDHB* led to increased proliferation and EMT. This was found to occur through

Fig. 2 Complex II in the electron transport chain. Electrons enter complex II. FAD is then reduced to FADH₂, during the oxidation of succinate to fumarate in SDHA. Electrons are transferred from FADH₂ to iron sulfur proteins in SDHB, and then to ubiquinone (Q) bound to SDHC and SDHD. Ubiquinone is reduced to ubiquinol (QH₂), which transfers electrons to complex III [25]



transcriptional upregulation of genes involved in methylation, leading to a hypermethylated epigenome. SDHB deficiency also correlated with the downregulation of genes involved in oxidative phosphorylation, as well as increased utilization of glucose in the pentose phosphate pathway (PPP) and glutamine in the Krebs cycle [42]. Of note, glutamine dependence correlates with invasion potential in ovarian cancer cells [43]. In mouse chromaffin cells, *SDHB* knockdown led to the activation of transcription factors important in EMT, which are also preferentially expressed in PPGLs. The cells took on an invasive phenotype, appearing to have undergone EMT [44].

The SDHC subunit has also been linked to EMT. In breast cancer tumors, increased expression of EMT genes, such as *TWIST* and *SNAI2* (*SLUG*), has been correlated with decreased expression of *SDHC*. Moreover, knockdown of *SDHC* in breast cancer cells using the CRISPR/Cas9 system induced EMT. *SDHC*-deficient breast cancer cells had increased expression of mesenchymal markers, such as vimentin and *TWIST*, as well as decreased expression of the epithelial marker, E-cadherin. Morphologically, these cells had decreased cell-cell adherence and stability in size, which is more in line with a mesenchymal phenotype. Furthermore, overexpression of *TWIST* and *SNAI2* caused decreased expression of SDH, as well as decreased mitochondrial respiration and biomass [45].

6 Genetic mutations in SDH-deficiency

6.1 Mutations in SDHA

SDHA is the most common mutation leading to SDH-deficient GIST, occurring in up to 30% of cases [46]. Loss of function mutations of *SDHA* were first identified in an isolated case of abdominal paraganglioma [47]. In 2011, sequencing of sporadic non-*KIT/PDGFR*A-mutated GIST revealed germline mutations in *SDHA* [48]. Miettinen and colleagues further

classified these *SDHA* germline mutations using immunohistochemistry. Tumors with *SDHA* mutations were found to be devoid of mutations in the other SDH subunits. However, these tumors were SDHB-deficient on immunohistochemistry, making this a reliable tool for identifying *SDHA*-mutant GISTs. Patients with *SDHA*-mutant tumors tend to have an older median age (34 years old) versus SDH-deficient GIST from other subunit mutations (21 years old) [46].

With the increased use of molecular testing and next-generation sequencing (NGS), many *SDHA* variants of unknown significance (VUS) have been identified. In 2017, Bannon and colleagues reported the creation of a yeast model to determine the functional significance of 22 of these variants on mitochondrial function. Their screen identified pathogenic VUS sequences that resulted in decreased expression of SDH and defective oxidative phosphorylation. They determined that 16 (73%) of the alterations are actually pathogenic, resulting in loss of SDH function. The remaining six (27%) have no effect on SDH function [49]. Thus, we continue to learn about the functional significance and previous underappreciation of these alterations.

6.2 Mutations in SDHB, C, and D subunits

Defects of other *SDHx* genes in non-*KIT/PDGFR*A mutated GIST were first reported in 2011 by Janeway and colleagues. This group demonstrated germline mutations in *SDHB* and *SDHC* lead to deficient SDHB expression, while most *KIT*-mutated GISTs have conserved expression of SDHB protein [18]. Germline mutations in *SDHB*, *SDHC*, and *SDHD* occur in only 20–30% of SDH-deficient GIST [24]. Currently, SDHB immunohistochemistry is used to identify all SDH-deficient GIST.

6.3 Epigenetic mutations in SDHC

Almost 50% of SDH-deficient GIST lack mutations in the genomic sequencing of *SDHx* subunits. However, DNA

methylation analyses of SDH-deficient GIST have revealed hypermethylation of the *SDHC* promoter sequence. The frequency of *SDHC* hypermethylation in non-*KIT/PDGFRA*-mutated GIST appears to be similar to that of coding mutations in *SDHx* subunit sequences. There are no reported simultaneous cases of *SDHC* genomic mutation and hypermethylation [50].

Epigenetic mutations in *SDHx* are also seen in the Carney Triad, a GIST syndrome in young females notable for development of gastric GIST, pulmonary chondroma, and paraganglioma [51]. The features of concurrent GIST and paragangliomas, as well as loss of SDHB by immunohistochemistry, are shared with Carney-Stratakis Syndrome. However, no germline mutations in *SDHx* have been identified in Carney Triad patients, suggesting that it is not a heritable condition. Tumors in these patients exhibit hypermethylation of the *SDHC* promoter sequence, leading to loss of SDHC protein expression and functional SDH deficiency [52, 53]. The identification of this hypermethylation phenomenon raises the hypothesis that demethylating agents may have therapeutic potential in SDH-deficient GIST.

7 Surgical management of SDH-deficient GISTs

Surgical resection continues to be a mainstay of treatment for all GISTs [54]. Generally, surgical resection of primary tumors is considered when the tumor is bleeding, causing obstruction, larger than 2 cm, or is increasing in size [55]. Resection of primary tumor with negative margins is achieved in 85% of patients, but recurrence or progression within 5 years is common. This suggests that surgical resection alone is not adequate for curative treatment of GIST [56]. Currently, guidelines do not exist for surgical management of GIST based on genetic mutations.

Only recently has the population of pediatric GIST patients been identified as a group of patients with genetically distinct tumors that likely require unique treatment approaches. The majority of pediatric patients have non-*KIT/PDGFRA*-mutated GIST [57]. Most treatments for pediatric GIST take place in the context of clinical trials and tertiary care centers [58]. Surgical resection is aimed at an organ-sparing resection of primary tumor. Given the increased incidence of lymph node metastases in non-*KIT/PDGFRA*-mutated GISTs, sampling of draining lymph node basins is recommended [22]. Close follow-up after surgery is also necessary due to high recurrence rates [58].

A retrospective study of young adults and adolescents with GIST in the SEER database showed that this population was more likely to receive surgical treatment. Young adults and adolescents had improved overall survival, as well as GIST-specific survival following surgical resection. In the same

study, it was found that GIST located in the stomach had poorer outcomes than those found in the small intestine [59]. It is noteworthy that SDH-deficient GIST is primarily found in the stomach. However, this study did not include stratification by genetic mutations limiting its application to the treatment for SDH-deficient GIST.

In 2017, the results of a retrospective analysis from the NIH Pediatric and Wild-type GIST clinic were reported [60]. This study was the first to evaluate surgical management of exclusively non-*KIT/PDGFRA* mutated GISTs. Analysis of 76 patients who underwent surgery found median event-free survival (EFS) to be 2.5 years with 71% of patients experiencing tumor recurrence or disease progression. The EFS was negatively affected by an elevated mitotic index and by the presence of metastases. Interestingly, negative resection margins and neoadjuvant or adjuvant treatment did not appear to affect EFS. SDH-deficient and SDH-competent tumors were only stratified for the outcome of EFS in a limited number of patients, with other variables such as metastases not being evaluated. Taken together, the results suggest that surgical resection of non-*KIT/PDGFRA*-mutated tumors may not be of benefit to some patients. However, given the inherent limitations of retrospective analysis, it is difficult to make any definitive recommendations for the surgical management of SDH-deficient GIST from the available data. But, with all surgical decision making, the morbidities should be weighed against the benefits of resection on an individualized basis.

8 Medical management of SDH-deficient GIST

8.1 Use of tyrosine kinase inhibitors

The tyrosine kinase inhibitor (TKI) imatinib is used as adjuvant therapy after surgical resection in high-risk patients treated with curative intent and as first-line systemic therapy for metastatic patients [54, 61]. Although imatinib is very effective in treating *KIT/PDGFRA*-mutant GISTs, SDH-deficient GISTs are largely resistant to TKIs due to the absence of gain-of-function tyrosine kinase mutations [18, 62]. Sunitinib is a TKI approved for the treatment of imatinib-resistant GIST [63]. Sunitinib inhibits the ATP-binding domains of KIT and PDGFRA, a property shared with imatinib. Unlike imatinib, sunitinib also inhibits VEGFR, which leads to blockade of angiogenesis. Sunitinib has been shown to increase progression-free and overall survival in advanced non-*KIT/PDGFRA*-mutated GIST after imatinib failure, possibly due to these added anti-angiogenic properties [64]. Unfortunately, primary and secondary resistance to sunitinib develops in almost all GIST patients with a median of 24 months after initiation of first-line treatment and 6–9 months after second-line treatment. The TKI regorafenib is approved for treatment of GIST after failure of imatinib and sunitinib. In a phase II study

of third-line regorafenib, 2 out of 6 patients with SDH-deficient GIST had a partial response [65]. In a 2014 phase II study of another TKI targeting VEGFR, pazopanib, the authors describe a patient with SDH-deficient GIST who experienced a 20% reduction of tumor size after failing sixth-line therapy [66]. However, most current studies continue to demonstrate the limited efficacy of TKIs in SDH-deficient GIST (Table 1).

8.2 Chemotherapeutic agents and experimental approaches

Traditional cytotoxic chemotherapy has had limited success in GIST patients. One example is temozolomide, an alkylating agent with demonstrated anti-tumor activity in soft tissue sarcomas [67]. Temozolomide appears to be ineffective in treating unselected GIST patients. Two different studies have evaluated the efficacy of temozolomide in GIST patients, both showing an objective response rate of 0% [68, 69]. However, a 2014 study of 15 patients with paraganglioma and pheochromocytoma demonstrated that 50% of *SDHB*-mutated patients had a partial response to temozolomide by RECIST 1.1 criteria [70, 71]. On the other hand, 0% of the *SDHB* wild-type patients had partial responses, with 40% having stable disease and 60% having progressive disease [70]. This suggests that *SDHB* mutations may be a biomarker for temozolomide sensitivity in paraganglioma and pheochromocytoma. The response of temozolomide has yet to be formally tested in SDH-deficient GIST patients. However, given SDH-deficient GIST and hereditary paragangliomas/pheochromocytomas share genomic mutations and inheritance patterns, we speculate that SDH-deficient GIST may have a response to temozolomide treatment. Our group at UC San Diego has recently opened Phase II clinical trial to investigate this hypothesis (ClinicalTrials.gov identifier NCT03556384).

As discussed above, hypermethylated promoter sequences in the *SDHC* gene leads to SDH deficiency. Furthermore, SDH deficiency in paragangliomas has been linked to the hypermethylation of target genes involved in chromaffin cell differentiation [72]. Thus, the use of DNA hypomethylating agents is under investigation for SDH-deficient cancers. A phase II clinical trial of the DNA methyltransferase inhibitor, guadecitabine, is currently recruiting participants with non-*KIT/PDGFR*A-mutated GIST and SDH-deficient paragangliomas and pheochromocytomas (ClinicalTrials.gov identifier NCT03165721).

Although the body of literature on the management of SDH-deficient GIST is limited, the increasing fund of knowledge regarding the metabolic role of SDH may lead to novel treatment approaches. A HIF2 α small molecule inhibitor, PT2385, has recently been identified and has been shown to act as a transcription factor-specific antagonist, inhibiting the expression of HIF2 α -specific genes. In mice with renal cell

Table 1 Clinical studies of FDA-approved TKI efficacy in SDH deficient or non-*KIT/PDGFR*A-mutated GIST

Author	Journal	Year	Study	Genetic profile	Imatinib	Regorafenib	Sunitinib	Vandetanib	Type of response
Boikos	<i>JAMA Oncology</i>	2016	Retrospective cohort study	SDH- deficient	1/49 (2.0%)		7/38 (18.4%)		Imatinib: 1 partial Sunitinib: 1 complete, 3 partial, 3 mixed.
Ben Ami	<i>Annals of Oncology</i>	2016	Phase II study	SDH-deficient		2/6 (33.3%)			Partial response
Janevay	<i>Ped Blood Cancer</i>	2009	Treatment use protocol	Non- <i>KIT/PDGFR</i> A mutant			1/7 (14.3%)		Partial response
Heinrich	<i>JAMA Oncology</i>	2017	SWOG S0033 Phase III study	SDH-deficient	1/12 (8.3%)				Partial response
Glod	<i>JCO</i>	2016	Phase II study	Non- <i>KIT/PDGFR</i> A mutant				0/9 (0%)	

carcinoma, treatment with PT2385 significantly reduced tumor burden [73]. In a recent phase I study of heavily pretreated clear cell renal carcinoma patients, PT2385 showed a favorable side effect profile and some efficacy, with an observed 14% objective response rate [74]. Given SDH deficiency is implicated in HIF1 α stabilization in tumor cells, anti-hypoxics may play a role in SDH-deficient GIST treatment.

8.3 Current guidelines for genetic testing and surveillance

According to the 2019 NCCN guidelines for soft tissue sarcomas, *KIT* and *PDGFRA* genetic testing should be considered for all patients with GIST that are to be treated with systemic agents. Subsequently, for non-*KIT/PDGFRA* mutated GISTs, SDHB immunohistochemistry is recommended. Germline testing is recommended for all SDH-deficient GISTs.

Currently, there are no clear surveillance guidelines for follow-up for SDH-deficient GIST, but follow-up should parallel that of the general GIST population. For all GIST patients with completely resected disease, follow-up with physical exams and cross-sectional imaging (i.e., CT or MRI) of the abdomen/pelvis is recommended every 3–6 months for the first 5 years and then annually.

Given their predisposition to various cancers, there is a question of whether asymptomatic *SDHx* mutation carriers require surveillance. Recently, the results were reported of an annual surveillance program of 65 asymptomatic *SDHB* mutation carriers at a tertiary care center in the UK. All patients underwent annual MRIs of the abdomen with every other year MRIs of the neck, pelvis, and thorax. Within 6 years, 25% had developed *SDHB*-related cancers with 16.6% having an asymptomatic tumor at the time of their first surveillance scan [75]. Of note, *SDHB* mutations are associated higher rates of pheochromocytoma and paragangliomas (PPGLs) [76, 77]. Patients with *SDHD* mutations were found to have a younger age of penetrance and were more likely to develop multifocal disease [78, 79]. In addition, *SDHB*- and *SDHD*-mutant PPGLs often secrete norepinephrine and dopamine or secrete only dopamine [80, 81] (dopamine-only [82, 83]). Currently, there is no available data regarding surveillance in *SDHA* and *SDHC* mutation carriers. However, given the difference in malignancy phenotypes between *SDHB* and *SDHD* mutation carriers, the argument can be made that surveillance recommendations should take into account which SDH subunit is mutated [84].

9 Conclusion

SDH-deficient GISTs are largely resistant to tyrosine kinase inhibitor therapy and lack effective treatment options. However, the understanding of the role of succinate

dehydrogenase in tumorigenesis continues to expand. This knowledge can be applied to develop novel treatment approaches to SDH-deficient GIST with an emphasis on the use of precision medicine to treat this unique set of cancers.

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Compliance with ethical standards

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