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Interplay between fatty acids, SCD, mTORC1 and YAP/TAZ in promoting hepatocellular carcinoma

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Abstract
Nonalcoholic fatty liver disease (NAFLD) has reached pandemic proportions with one of its most consequential complications being hepatocellular carcinoma (HCC). NAFLD-related HCC is becoming the leading indication for liver transplantation in the USA. Given the scarcity of available organs, early detection and prevention remain key in prevention and management of the disease. Over the years, the YAP/TAZ pathway emerged as a key signal transduction pathway in the pathogenesis of HCC. In this review, we explore the interplay between the YAP/TAZ pathway as a point of convergence in HCC pathogenesis. We review the evidence of how lipid reprogramming and key lipid pathways, saturated and monounsaturated fatty acids (through the rate limiting enzyme stearoyl Co-A desaturase), the mevalonic acid pathway (the role of statins) and mTORC1 all play critical roles in intricate and complex network that tightly regulate the YAP/TAZ pro-oncogenic pathway.
**Introduction**: Primary liver cancer is the second leading cause of cancer death worldwide. Hepatocellular carcinoma (HCC), which comprises 90% of the cases, commonly presents in patients with hepatic fibrosis associated with chronic hepatitis B virus (HBV) or hepatitis C virus (HCV), excessive alcohol consumption, or metabolic syndrome (MetS). **Error! Hyperlink reference not valid.** As described below, the genetic landscape of HCC is complex and includes mutations in the Wnt/β-catenin (CTNNB1) pathway, chromatin remodeling, telomere maintenance and inactivation of p53.

**Nonalcoholic fatty liver disease associated HCC burden**: In the USA, liver cancer incidence rates have more than tripled since 1980, while the cancer-associated death rates have more than doubled during this time. In parallel, non-alcoholic fatty liver disease (NAFLD), a common condition in patients with obesity and type 2 diabetes (T2D), has reached pandemic proportions and continues to rise. In the era of direct-acting antiviral therapy for HCV and improved HBV treatment, NAFLD-HCC is predicted to become the leading indication for liver transplantation (LT). As LT remains a scarce resource with recent evidence suggesting that HCCs are transplanted less often following changes in United States Organ Procurement Network policy, understanding its underlying mechanisms is of utmost importance to develop and implement chemoprevention and early detection programs, as well as tailor treatment approaches.

NAFLD and HCC are complex diseases that result from genetic and environmental interactions. Many clinical potentially modifiable risk factors have been associated with NAFLD-HCC development, including features of the MetS, as defined by the clustering of T2D, hypertension, dyslipidemia and obesity, where each condition plays an additive or synergistic role in the pathogenesis of NAFLD-HCC. Although statins are commonly prescribed for the treatment of dyslipidemia and the MetS, their use has been shown to be protective in all etiologies of HCC, including in non-alcoholic steatohepatitis (NASH), the more severe form in the NAFLD spectrum.

The mechanisms involved in NAFLD-related HCC pathogenesis are therefore of major fundamental and translational importance but remain incompletely understood. In a large Veteran population, the estimated incidence of HCC in the patients with NAFLD is 0.21/1000 person-years (PY), with the highest incidence occurring in the sub-population of patients with cirrhosis (10.6/1000 PY). Simon et al. demonstrated similar findings in a European population-based cohort of biopsy-proven NAFLD and NASH, where HCC occurred at
an incidence of 6.2/1000 PY for patients with underlying cirrhosis (95% CI 4.2-8.8/1000 PY). The incidence of HCC was lower for patients with biopsy-proven simple steatosis (n=5,939) at 0.8/1000 PY, and NASH without fibrosis (n=1,050) at 1.2/1000 PY. The differences in incidence and disease progression likely reflect the heterogeneity in the NAFLD population, and potentially non-modifiable genetic differences, and their gene-environment interactions. There is evidence from previous genome wide association studies (GWAS) demonstrating a predominance of NAFLD in Hispanic patients, followed by Caucasians and African Americans, which have been further substantiated in the HCC population. Unlike viral and ethanol-associated causes of HCC, NAFLD patients represent a distinct high-risk population where 20-30% of all HCCs occur in the absence of cirrhosis. Although current guidance does not recommend HCC screening in patients without cirrhosis, the estimated disease burden globally and health care-associated costs, prompt the need for further research in this population, as outlined by recent professional society recommendations.

**Mutations in HCC development:** Heritability of NAFLD and NASH has been suggested based on early observations of the clustering of disease in families and twins. In NAFLD-related HCC, teasing out inherited genetic contributions from chronic fibrosis/cirrhosis versus NAFLD-specific causes using GWAS remains a challenge and is still being investigated. Independently of its genetic predisposing factors, HCC often results from an accumulation of somatic mutations that lead to tumor initiation and progression. Studies have demonstrated that each HCC has about 40-60 somatic mutations, several of which converge on key molecular pathways. Many mutations affect telomere maintenance (TERT or telomere reverse transcriptase activation); WNT activation (mutation in CTNNB1 which encodes β-catenin, APC and AXIN1); the tumor suppressor p53 gene (TP53); chromatin remodeling (including in the AT-rich interaction domain 1A or ARID1A); activation of the PI3K/mechanistic target of rapamycin (mTORC1); and activation of receptor tyrosine kinases. The majority of mutations identified have been shown not to be actionable therapeutically. Of the multiple pathways identified, certain ones deserve special attention because of their common occurrence. For instance, β-catenin activation through point mutations of CTNNB1 and mutation of TP53 occur in up to 50% HCC cases. HCCs can be sub-classified into proliferation and non-proliferation classes with some overlaps in the mutational landscape, including in β-catenin activation. An emerging area of interest is the interplay among lipid
metabolism, mTORC1 and the Hippo pathway in HCC. These represent major foci of this article, which are discussed in subsequent sections.

The lipid environment and NAFLD-related HCC: It is widely accepted that growing cells require unsaturated fatty acids and cholesterol as essential building blocks for biogenesis of cellular membranes. Early on investigators observed that cancer cells also synthesize lipids. Lipids, and specifically fatty acids, have been shown to have an integral role in changing the tumor environment (TME) to meet the demands of rapid cell proliferation observed in cancer cells, where oxygen and nutrients are scarce. This hallmark of cancer cells has been termed ‘metabolic reprogramming’, and has been linked to clinical aggressiveness of many tumors. This is supported by a large body of evidence that suppression of lipogenic pathways decreases cell growth in both in vitro and in vivo models. Understanding tumor lipid metabolism and the crosstalk between the lipidome and the pathways that drive HCC has therefore advanced the targeting of lipid pathways in cancer treatments and includes the use of fatty acid synthase (FASN) TVB-2640 for non-small cell carcinoma (NCT03808558), high-grade sarcoma (NCT03032484) and triple-negative breast cancer (NCT03179904), which are all currently investigated in clinical trials.

The study of the lipidome has only recently been extended to understanding the role of lipids in the pathogenesis of HCC. Most human studies have been conducted in viral etiologies of HCC and have focused on urine and serum lipid analyses with the aim to understand tumor biology and develop clinical biomarkers. Given that serum and tissue lipids measurements are not always concordant, other studies have focused on understanding the lipid profile of the HCCs and adjacent non-tumor tissue controls. Few lipidomic studies have been conducted in NAFLD-HCC patients. Lewinska et al. recently studied the serum lipidome profile of patients with NAFLD-HCC (n=27) and compared it to ethanol and viral etiologies of HCC (AV-HCC; n=32), morbidly obese patients (OB-NAFLD; n=102) and healthy controls (n=35). Compared to AV-HCC and OB-NAFLD, NAFLD-HCC patients had higher triglycerides (47.0 and 45.1) and phosphatidylcholine (16:0/17:0, 18:2/0:0, 0:0/18:2) levels but lower monounsaturated fatty acids (MUFA), polyunsaturated fatty acids (PUFA) and linoleic acid, after adjusting for age, sex and body mass index (BMI). The authors propose that the lower MUFA and PUFA pool may be related to an increase uptake of these lipid species by the HCCs from the serum to sustain their growth and proliferation. Consistent with these findings, Muir et al., identified that stearoyl-Co-A
desaturase (SCD), the rate-limiting enzyme in the conversion of saturated fatty acids (SFA) to MUFAs, which is preferentially found on the endoplasmic reticulum, was upregulated in human NAFLD-related HCC samples and Pten-null NASH-HCC murine models. While unsaturated fatty acids are required for cellular proliferation and membrane biogenesis, fatty acids also play important signaling functions that remain much less understood.

**SCD, mTORC1 and HCC:** As indicated above, SCD plays a critical role in regulating the ratio of unsaturated/saturated fatty acids. MUFAs represent the precursors of the main components of cellular membranes and are crucially important in the pathogenesis of the MetS, NAFLD, NASH and HCC pathogenesis. This is supported by clinical studies demonstrating worse overall survival of patients with HCCs who demonstrate a high SCD expression, compared to HCCs with low SCD expression. Consistent with SCD playing a critical role in HCC tumor growth, Bansal et al. demonstrated the inverse relationship between SCD gene expression patterns and HCC tumor differentiation. Similarly, the role of SCD in HCC is further supported by an elevated serum saturated to unsaturated phosphatidylcholine (16:0/16:1) level in patients with cirrhosis and HCC. Mechanistic studies of SCD and MUFAs in chronic liver disease point to selective effects of SCD on different resident liver cell types including M1 macrophage, hepatic stellate cells, and hepatocytes. These data suggest that the TME, supported by these other cell types, may play an integral role in HCC growth and aggressiveness. However, detailed human cell-type studies are lacking and have only recently been able to be identified with the advent of single cell and single nucleus RNA sequencing.

As shown in figure 1, SCD expression is regulated at multiple levels, including by the sterol regulatory element-binding protein 1 (SREBP1), the master transcription regulator of lipid biosynthesis, which has higher expression in HCC through mammalian target of rapamycin (mTOR) signaling. mTOR functions as a catalytic subunit in two distinct multi-protein complexes, the mechanistic target of rapamycin 1 (mTORC1), characterized by the subunit, Raptor (regulatory-associated protein of mTORC1) and mTORC2, characterized by the subunit Rictor (Raptor-independent companion of mTORC2). The heterodimer of the tumor suppressor TSC1 and TSC2 represses mTORC1 activity by acting as the GTPase activating protein for Rheb, a potent activator of mTORC1 in its GTP-bound state (Fig. 1). Using an interactive open-access database (www.proteinatlas.org/pathology), we found that higher expression of Rheb is significantly associated with poor survival in HCC (Fig. 2A). In the presence of amino acids, activated Akt and/or ERK/p90RSK phosphorylate and uncouple TSC1/TSC2 from
Rheb, leading to Rheb-GTP accumulation and mTORC1 activation at lysosomal membranes, which then promotes cell growth. Ragulator complex proteins LAMTOR 1, 3 and 5, which are involved in amino acid sensing and mTORC1 activation are also significantly associated with unfavorable prognosis (survival) in HCC (Fig. 2B-D). The association of Rheb and LAMTORS1, 3 and 5 with unfavorable prognosis emphasizes the importance of mTORC1 function in HCC development. In turn, mTORC1 increases lipogenesis through regulation of SREBP1 at several levels, including trafficking, processing, and transcription. SREBP1 induces the expression of lipogenesis genes, including SCD.

**SCD and MUFAS in the control of the Hippo Pathway:** In recent years, the ratio of SFA to MUFAs has been implicated in the regulation of the highly conserved Hippo tumor-suppressor pathway and in the function of its downstream effectors in several cell types. The transcriptional co-activators Yes-Associated Protein (YAP) and its paralog WW-domain-containing Transcriptional co-Activator with PDZ-binding motif (TAZ) are critical effectors of the Hippo pathway and fundamental points of convergence and intersection of other signal transduction pathways implicated in the regulation of development, metabolism, organ-size, positional sensing, tissue regeneration and tumorigenesis. The canonical Hippo pathway is a serine/threonine kinase cascade wherein Mst1/2 kinases in complex with Sav1, phosphorylate and activate Lats1/2, in complex with its regulatory protein MOB1/2 (Fig. 1). In turn, LATS1/2 phosphorylate YAP and TAZ. Structurally, YAP and TAZ share nearly half of the overall amino acid sequence, have very similar topology and highly conserved residues located within a consensus sequence phosphorylated by Lats1/2 (HHRXXS). The phosphorylation of YAP by Lats1/2 at Ser-127 and Ser-397 (and equivalent residues in TAZ) restricts its cellular localization to the cytoplasm and reduces its protein stability. When the Hippo pathway is not functional, YAP and TAZ are dephosphorylated and translocate to the nucleus where they bind and activate a number of transcription factors, primarily the TEA-domain DNA-binding transcription factors (TEAD1-4). When the Hippo pathway is active, LATS1/2 phosphorylates YAP and TAZ at multiple sites, thereby restricting their cellular localization to the cytoplasm, thus preventing their interaction with TEADs. An increased expression of SAV1, a protein necessary for the function of Mst1/2 upstream in the Hippo tumor-suppressive pathway, is associated with favorable prognosis in HCC (Fig. 2E), whereas, reciprocally, the expression of BIRC5 and TEAD2 has
been associated with poor overall survival in HCC (Fig. 2, F, G). BIRC5, which encodes survivin, a potent inhibitor of apoptosis and a downstream target of YAP\(^{59}\). In addition, it is emerging that the Mobs are a family of proteins with positive and negative effects on the Hippo pathway\(^{60}\). Accordingly, high expression of Mob 4, a component of the multi-subunit protein complex STRIPAK (Striatin-interacting phosphatase and kinase) that negatively regulates the Hippo pathway\(^{60,61}\), is associated with unfavorable prognosis in HCC (Fig. 2H).

In line with the associations identified above, several studies in preclinical models indicate that YAP/TAZ play a major role in promoting HCC. An early study demonstrated that YAP overexpression in the liver induces rapid HCC development, implying a potent oncogenic role of this protein\(^{62}\). Further studies using liver-specific knock out of Mst1/2 or Sav1 demonstrated that the Hippo signaling pathway is a critical regulator of mammalian liver growth and a potent suppressor of liver tumor formation\(^{63}\). Reciprocally, heterozygous knock out of YAP in mouse models, suppressed the development of HCC-like tumors\(^{64}\). Subsequent multiple studies substantiated that the tumor suppressive Hippo pathway plays a critical role in liver regeneration\(^{65}\) and drug resistance\(^{66,67}\). Furthermore, YAP promotes mTORC1 activation via downregulation of PTEN and increase in amino acid uptake\(^{68}\). In turn, mTORC1 leads to YAP/TAZ accumulation through inhibition of GSK3\(\beta\)\(^{69}\), thus establishing a positive feedback loop (Fig. 1). A fundamental crosstalk of the Hippo-YAP pathway with multiple metabolic pathways has been reviewed recently\(^{70}\). The Hippo YAP/TAZ signaling pathway has also been implicated in changing the TME in pancreatic adenocarcinoma, including in macrophages, highlighting the multi-faceted role and complex interplay of the Hippo-YAP pathway between cells in cancer development and progression\(^{71}\).

Emerging evidence supports the importance of lipid regulation of the Hippo pathway. In endothelial cells, palmitic acid, the most common of the SFA, induces expression of the Hippo pathway kinase Mst1 leading to YAP phosphorylation and nuclear export, therefore inhibiting nuclear YAP function\(^{72}\). Reciprocally, in primary human lung adenocarcinoma cells knockdown or pharmacological inhibition of SCD impairs the function of YAP and TAZ, implying a positive role of MUFAs in YAP/TAZ activation\(^{73}\). Despite these advances, the mechanisms of YAP/TAZ in HCC remain poorly understood, especially in response to lipid dysregulation and their effects on the tumor microenvironment in different resident cell-types of the liver.

**Palmitoylation of TEADs transcription factors**: Palmitic acid is a saturated fatty acid with important properties in the MetS\(^{74}\), including in NAFLD and NASH\(^{75}\) that regulates expression of Hippo kinases (see above). Many
proteins have been shown to undergo post-translational modification by S-palmitoylation, including those involved in membrane trafficking and cellular localization\textsuperscript{76, 77}. Using a series of biochemical and genetic approaches, Chan \textit{et al.} demonstrate that TEADs are autopalmitoylated at conserved cysteine residues, which in turn indirectly regulate YAP and TAZ by changing the conformation of TEAD proteins and therefore affecting their downstream association with these co-activators\textsuperscript{78}. It was subsequently shown that S-palmitoylation is key in the homeostasis of TEAD protein levels in cells, thus providing another layer of regulation of the Hippo pathway\textsuperscript{79}. FASN is key in the synthesis of palmitoyl-CoA. Thus, it is conceivable that the FASN benefits observed in early clinical trials for non-small cell carcinoma, breast cancer and sarcoma (see “the lipid environment and NAFLD-related HCC”), may be partially due to inhibition of this autophosphorylation loop, which in turn dampens the YAP/TAZ oncogenic pathway. Although this concept is starting to be investigated in HCC \textit{in vitro} cell culture models\textsuperscript{80}, it remains an understudied area of HCC development of progression, especially in the context of NAFLD and NASH where intrahepatic lipid content is high. TEAD palmitoylation is a topic attracting interest as inhibitors of this critical modification are being developed\textsuperscript{79, 81} that could offer novel therapeutic approaches in HCC and other cancers.

**YAP, TAZ and HCC:** Although YAP has been investigated and linked to many malignancies, its role in HCC pathogenesis is only emerging\textsuperscript{82-86}. In a predominant viral hepatitis cohort, patients with high YAP expression in HCCs (n=177) were more likely to have poorly differentiated HCCs, which was associated with >2-fold increase in HCC-specific death\textsuperscript{87}. Consistent with the mechanism of action of YAP, most tumors (62% had YAP expression) showed nuclear YAP localization\textsuperscript{87}. A recent study uncovered that YAP and TAZ have overlapping and distinct roles in the development of liver carcinogenesis\textsuperscript{88}. Several signaling pathways interact and cross-talk in cancer development to sustain tumor growth, including with YAP. Molecular subclassifications of HCC have been described\textsuperscript{21, 29}. One commonly mutated pathway that has been shown to converge on the YAP/TAZ pathway is the Wnt-β-catenin signaling pathway which affects 30-50% of all cases\textsuperscript{21, 50, 84}. Mechanistic studies linking YAP/TAZ to Wnt-β-catenin signaling pathway suggest that this regulation occurs, at least in part, indirectly\textsuperscript{84} through SCD and the MUFA/SFA intracellular pool\textsuperscript{50}. Lai and colleagues elegantly demonstrate this \textit{in vivo} and \textit{in vitro} models where SCD was over-expressed both in activated hepatic stellate cells and hepatocytes. The Wnt-β-catenin in turn increased SREBP1, which stabilized
LRP5 and LRP6 via MUFA intracellular pools and promoted liver fibrosis and HCC development. These data further support TME cross-talk with hepatocytes for HCC pathogenesis.

Although several studies have focused on the role of YAP in HCC, TAZ may play a more important role in the transition from steatosis to NASH and fibrosis, which are precursors to HCC development. TAZ protein was found to be higher in human liver samples and a NASH murine models (methionine/choline deficiency-MCD- or fructose, palmitate, cholesterol-FPC-), compared to controls, with its silencing leading to reversal of inflammation, cell death and even fibrosis (through stellate cell activation). The crosstalk between these pathways and convergence on the YAP pathway need further exploration.

**Mevalonate pathway in the control of YAP/TAZ:** Statins are among the most widely prescribed medications in the world to treat dyslipidemia. Although most research on the effects of statins has been in the context of cardiovascular or metabolic diseases, recent large epidemiological studies, including in Veterans, indicate a protective effect of statins administration in HCC and other malignancies. Specifically, lipophilic statins are associated with a decrease in the incidence of HCC and its associated mortality, compared to hydrophilic statins and non-users. Although prospective and randomized control trials are ongoing to assess their clinical utility, the mechanism(s) involved remain poorly understood. Statins are specific inhibitors of the 3-hydroxy-methylglutaryl (HMG) CoA reductase, the rate-limiting enzyme in the generation of mevalonate, the first step in the biosynthesis of isoprenoids, leading to farnesyl pyrophosphate (FPP), geranylgeranyl pyrophosphate (GG-PP) and cholesterol. The transfer of the geranylgeranyl moiety to a COOH-terminal cysteine of Rho GTPases is critical for their function in signal transduction. Indeed, as depicted in Fig. 1, active Rho (i.e. Rho-GTP) is essential for YAP/TAZ activation, at least in part through actin remodeling and modulation of the STRIPAK multi-subunit complex. A recent study found that the endoplasmic reticulum (ER) protein Nogo-B, is highly expressed in both murine and human NAFLD-associated HCCs and leads to lysophosphatidic acid (LPA)-enhanced YAP oncogenic activity. LPA is known to stimulate YAP via G protein-coupled receptors that promote Rho activation. Another study concluded that YAP directly interacts with SREBP1c and SREBP2 on the promoters of the FASN and HMG CoA reductase, thereby stimulating their transcription and promoting hepatocyte lipogenesis and cholesterol synthesis. Several studies linked mevalonate metabolism and YAP/TAZ activity and identified lipophilic statins as YAP/TAZ inhibitors in a variety of cell types but the
impact of statins on YAP localization, phosphorylation and activity in HCC cells remains unknown. The possibility that statins impair actin remodeling and/or STRIPAK activity in response to multiple agonists and growth factors that induce Rho activation (i.e. conversion of Rho-GDP to Rho-GTP) are intriguing molecular mechanisms in the context of HCC and other cancers but remain untested. Interestingly, it has been identified that the ATP-binding cassette (ABC) A1 transporter (ABCA1) is a target gene of p53. Activation of ABCA1 results in reverse cholesterol transport, which leads to decreased SREBP2, the master transcription factor of cholesterol biosynthesis, which in turn leads to repression of the mevalonic acid pathway.

Conclusions: Treatment of advanced and unresectable HCC has greatly changed over the recent years with the advent of immunotherapy and advances in locoregional therapies. For decades, Sorafenib, a multi-protein kinase inhibitor, was first-line for treatment of advanced HCC. Its long-standing use informed patterns of resistance and how it affected HCC recurrence. In the context of this discussion, it is of interest that several recent studies identified YAP as a major mediator of HCC resistance to Sorafenib. Similarly, Hippo signaling has been recently been shown to be a target of Regorafenib, which has a similar mechanism of action to Sorafenib, resistance in HCC using a CRISPR-Cas9 screen.

In the light of the signaling network discussed herein, the exciting possibility of synergism between statins, SCD inhibitors, mTORC1 inhibitors (including rapamycin and its analogues) and kinase inhibitors in dampening HCC cell proliferation and migration and preventing drug resistance through inhibition of YAP/TAZ is a novel therapeutic approach that has not been examined in HCC. Additionally, the use of lipid modulators including statins as chemoprevention methods for NAFLD-related HCC should be further explored to tackle the large healthcare and economic burdens anticipated in the near future. Finally, understanding the HCC subclassifications through these different pathways may help explain the heterogeneity of HCC development and treatment responses, and would advance the role of precision oncology, especially in NAFLD-HCC, which has distinct features compared to its viral counterparts.
**Figure 1**- Proposed model for cross talk of different pathways converging on the YAP/TAZ pathway in HCC pathogenesis.

**Figure 2**- Kaplan-Meier plots for gene expression of the signaling network in HCC. Images were reproduced from the Human Protein Atlas (version 17) available from www.proteinatlas.org.

Transcriptomics data was available from 365 patients in total with 119 female and 246 male patients. A majority of patients (n=235) were still alive at the time of data collection. The stage distribution was i) 170 patients, stage ii) 84 patients, stage iii) 83 patients, stage iv) 4 patients and 24 patients with missing data information. The links to the specific genes shown are as follows:

Rheb: https://www.proteinatlas.org/ENSG00000106615-RHEB/pathology/liver+cancer/

LAMTOR1: https://www.proteinatlas.org/ENSG00000149357-LAMTOR1/pathology/liver+cancer

LAMTOR3: https://www.proteinatlas.org/ENSG00000109270-LAMTOR3/pathology/liver+cancer

LAMBOR5: https://www.proteinatlas.org/ENSG00000134248-LAMTOR5/pathology/liver+cancer

SAV1: https://www.proteinatlas.org/ENSG00000151748-SAV1/pathology/liver+cancer

BIRC5: https://www.proteinatlas.org/ENSG00000089685-BIRC5/pathology/liver+cancer

TEAD2: https://www.proteinatlas.org/ENSG00000074219-TEAD2/pathology/liver+cancer

Mob4: https://www.proteinatlas.org/ENSG00000115540-MOB4/pathology/liver+cancer
References:

1. Sung H, Ferlay J, Siegel RL, et al. Global Cancer Statistics 2020: GLOBOCAN Estimates of Incidence and Mortality Worldwide for 36 Cancers in 185 Countries. CA Cancer J Clin 2021;71:209-249.
2. Estes C, Razavi H, Loomba R, et al. Modeling the epidemic of nonalcoholic fatty liver disease demonstrates an exponential increase in burden of disease. Hepatology 2018;67:123-133.
3. Younossi ZM, Stepanova M, Ong J, et al. Nonalcoholic Steatohepatitis Is the Most Rapidly Increasing Indication for Liver Transplantation in the United States. Clin Gastroenterol Hepatol 2020.
4. Kwong AJ, Ghaziani TT, Mehta N. Decreased Urgency Among Liver Transplantation Candidates With Hepatocellular Carcinoma in the United States. Liver Transpl 2021.
5. Eslam M, Valenti L, Romeo S. Genetics and epigenetics of NAFLD and NASH: Clinical impact. J Hepatol 2018;68:268-279.
6. Simon TG, King LY, Chong DQ, et al. Diabetes, metabolic comorbidities, and risk of hepatocellular carcinoma: Results from two prospective cohort studies. Hepatology 2018;67:1797-1806.
7. Kanwal F, Kramer JR, Mapakshi S, et al. Risk of Hepatocellular Cancer in Patients With Non-Alcoholic Fatty Liver Disease. Gastroenterology 2018;155:1828-1837 e2.
8. Singh S, Singh PP, Singh AG, et al. Statins are associated with a reduced risk of hepatocellular cancer: a systematic review and meta-analysis. Gastroenterology 2013;144:323-332.
9. Simon TG, Duberg AS, Aleman S, et al. Lipophilic Statins and Risk for Hepatocellular Carcinoma and Death in Patients With Chronic Viral Hepatitis: Results From a Nationwide Swedish Population. Ann Intern Med 2019;171:318-327.
10. Kaplan DE, Serper MA, Mehta R, et al. Effects of Hypercholesterolemia and Statin Exposure on Survival in a Large National Cohort of Patients With Cirrhosis. Gastroenterology 2019;156:1693-1706 e12.
11. Pinyopornpanish K, Al-Yaman W, Butler RS, et al. Chemopreventive Effect of Statin on Hepatocellular Carcinoma in Patients With Nonalcoholic Steatohepatitis Cirrhosis. Am J Gastroenterol 2021;116:2258-2269.
12. Romeo S, Kozlitina J, Xing C, et al. Genetic variation in PNPLA3 confers susceptibility to nonalcoholic fatty liver disease. Nat Genet 2008;40:1461-5.
13. Trepo E, Caruso S, Yang J, et al. Common genetic variation in alcohol-related hepatocellular carcinoma: a case-control genome-wide association study. Lancet Oncol 2022;23:161-171.
14. Kanwal F, Kramer JR, Li L, et al. Effect of Metabolic Traits on the Risk of Cirrhosis and Hepatocellular Cancer in Nonalcoholic Fatty Liver Disease. Hepatology 2020;71:808-819.
15. Benhhamou JN, Aby ES, Shirvanian G, et al. Improved survival after treatments of patients with nonalcoholic fatty liver disease associated hepatocellular carcinoma. Sci Rep 2020;10:9902.
16. Huang DQ, El-Serag HB, Loomba R. Global epidemiology of NAFLD-related HCC: trends, predictions, risk factors and prevention. Nat Rev Gastroenterol Hepatol 2020.
17. Allen AM, Van Houten HK, Sangaralingham LR, et al. Healthcare Cost and Utilization in Nonalcoholic Fatty Liver Disease: Real-World Data From a Large U.S. Claims Database. Hepatology 2018;68:2230-2238.
18. Kanwal F, Shubrook JH, Younossi Z, et al. Preparing for the NASH epidemic: A call to action. Metabolism 2021:154822.
19. Schwimmer JB, Celedon MA, Lavine JE, et al. Heritability of nonalcoholic fatty liver disease. Gastroenterology 2009;136:1585-92.
20. Loomba R, Schork N, Chen CH, et al. Heritability of Hepatic Fibrosis and Steatosis Based on a Prospective Twin Study. Gastroenterology 2015;149:1784-93.
21. Llovet JM, Zucman-Rossi J, Pikarsky E, et al. Hepatocellular carcinoma. Nat Rev Dis Primers 2016;2:16018.
22. Llovet JM, Kelley RK, Villanueva A, et al. Hepatocellular carcinoma. Nat Rev Dis Primers 2021;7:6.
23. Chiang DY, Villanueva A, Hoshida Y, et al. Focal gains of VEGFA and molecular classification of hepatocellular carcinoma. Cancer Res 2008;68:6779-88.

24. Guegan JP, Lapouge M, Voisin L, et al. Signaling by the tyrosine kinase Yes promotes liver cancer development. Sci Signal 2022;15:eabj4743.

25. Takeda H, Takai A, Eso Y, et al. Genetic Landscape of Multistep Hepatocarcinogenesis. Cancers (Basel) 2022;14.

26. Hyman DM, Taylor BS, Baselga J. Implementing Genome-Driven Oncology. Cell 2017;168:584-599.

27. de La Coste A, Romagnolo B, Billuart P, et al. Somatic mutations of the beta-catenin gene are frequent in mouse and human hepatocellular carcinomas. Proc Natl Acad Sci U S A 1998;95:8847-51.

28. Khalaf AM, Fuentes D, Morshid AI, et al. Role of Wnt/beta-catenin signaling in hepatocellular carcinoma, pathogenesis, and clinical significance. J Hepatocell Carcinoma 2018;5:61-73.

29. Zucman-Rossi J, Villanueva A, Nault JC, et al. Genetic Landscape and Biomarkers of Hepatocellular Carcinoma. Gastroenterology 2015;149:1226-1239 e4.

30. Medes G, Thomas A, Weinhouse S. Metabolism of neoplastic tissue. IV. A study of lipid synthesis in neoplastic tissue slices in vitro. Cancer Res 1953;13:27-9.

31. Currie E, Schulze A, Zechner R, et al. Cellular fatty acid metabolism and cancer. Cell Metab 2013;18:153-61.

32. Beloribi-Djefaflia S, Vasseur S, Guillaumond F. Lipid metabolic reprogramming in cancer cells. Oncogenesis 2016;5:e189.

33. de Gonzalo-Calvo D, Lopez-Vilaro L, Nasarre L, et al. Intratumor cholesteryl ester accumulation is associated with human breast cancer proliferation and aggressive potential: a molecular and clinicopathological study. BMC Cancer 2015;15:460.

34. Guillaumond F, Bidaut G, Ouaisi M, et al. Cholesterol uptake disruption, in association with chemotherapy, is a promising combined metabolic therapy for pancreatic adenocarcinoma. Proc Natl Acad Sci U S A 2015;112:2473-8.

35. Svensson RU, Parker SJ, Eichner LJ, et al. Inhibition of acetyl-CoA carboxylase suppresses fatty acid synthesis and tumor growth of non-small-cell lung cancer in preclinical models. Nat Med 2016;22:1108-1119.

36. Xue R, Lin Z, Deng C, et al. A serum metabolic investigation on hepatocellular carcinoma patients by chemical derivatization followed by gas chromatography/mass spectrometry. Rapid Commun Mass Spectrom 2008;22:3061-8.

37. Chen F, Xue J, Zhou L, et al. Identification of serum biomarkers of hepatocellular carcinoma through liquid chromatography/mass spectrometry-based metabonomic method. Anal Bioanal Chem 2011;401:1899-904.
44. Lu Y, Li N, Gao L, et al. Acetylcarnitine is a Candidate Diagnostic and Prognostic Biomarker of Hepatocellular Carcinoma. Cancer Res 2016;76:2912-20.
45. Li Z, Guan M, Lin Y, et al. Aberrant Lipid Metabolism in Hepatocellular Carcinoma Revealed by Liver Lipidomics. Int J Mol Sci 2017;18.
46. Lewinska M, Santos-Laso A, Arretxe E, et al. The altered serum lipidome and its diagnostic potential for Non-Alcoholic Fatty Liver (NAFL)-associated hepatocellular carcinoma. EBioMedicine 2021;73:103661.
47. Muir K, Hazim A, He Y, et al. Proteomic and lipidomic signatures of lipid metabolism in NASH-associated hepatocellular carcinoma. Cancer Res 2013;73:4722-31.
48. Chiappini F, Coilly A, Kadar H, et al. Metabolism dysregulation induces a specific lipid signature of nonalcoholic steatohepatitis in patients. Sci Rep 2017;7:46658.
49. Walle P, Takkunen M, Mannisto V, et al. Fatty acid metabolism is altered in non-alcoholic steatohepatitis independent of obesity. Metabolism 2016;65:655-666.
50. Lai KKY, Kweon SM, Chi F, et al. Stearoyl-CoA Desaturase Promotes Liver Fibrosis and Tumor Development in Mice via a Wnt Positive-Signaling Loop by Stabilization of Low-Density Lipoprotein-Receptor-Related Proteins 5 and 6. Gastroenterology 2017;152:1477-1491.
51. Benhammou JN, Ko A, Alvarez M, et al. Novel Lipid Long Intervening Noncoding RNA, Oligodendrocyte Maturation-Associated Long Intergenic Noncoding RNA, Regulates the Liver Steatosis Gene Stearoyl-Coenzyme A Desaturase As an Enhancer RNA. Hepatol Commun 2019;3:1356-1372.
52. Porstmann T, Santos CR, Griffiths B, et al. SREBP activity is regulated by mTORC1 and contributes to Akt-dependent cell growth. Cell Metab 2008;8:224-36.
53. Dong J, Feldmann G, Huang J, et al. Elucidation of a universal size-control mechanism in Drosophila and mammals. Cell 2007;130:1120-33.
54. Suemura S, Kodama T, Myojin Y, et al. CRISPR Loss-of-Function Screen Identifies the Hippo Signaling Pathway as the Mediator of Regorafenib Efficacy in Hepatocellular Carcinoma. Cancers (Basel) 2019;11.
55. Zhou Y, Wang Y, Zhou W, et al. YAP promotes multi-drug resistance and inhibits autophagy-related cell death in hepatocellular carcinoma via the RAC1-ROS-mTOR pathway. Cancer Cell Int 2019;19:179.
56. Koo JH, Guan KL. Interplay between YAP/TAZ and Metabolism. Cell Metab 2018;28:196-206.
Bautista SJ, Boras I, Vissa A, et al. mTOR complex 1 controls the nuclear localization and function of glycogen synthase kinase 3beta. J Biol Chem 2018;293:14723-14739.

Ibar C, Irvine KD. Integration of Hippo-YAP Signaling with Metabolism. Dev Cell 2020;54:256-267.

Yang W, Yang S, Zhang F, et al. Influence of the Hippo-YAP signalling pathway on tumor associated macrophages (TAMs) and its implications on cancer immunosuppressive microenvironment. Ann Transl Med 2020;8:399.

Yuan L, Mao Y, Luo W, et al. Palmitic acid dysregulates the Hippo-YAP pathway and inhibits angiogenesis by inducing mitochondrial damage and activating the cytosolic DNA sensor cGAS-STING-IRF3 signaling mechanism. J Biol Chem 2017;292:15002-15015.

Noto A, De Vitis C, Pisanu ME, et al. Stearoyl-CoA-desaturase 1 regulates lung cancer stemness via stabilization and nuclear localization of YAP/TAZ. Oncogene 2017;36:4671-4672.

Resh MD. Trafficking and signaling by fatty-acylated and prenylated proteins. Nat Chem Biol 2006;2:584-90.

Chan P, Han X, Zheng B, et al. Autopalmitoylation of TEAD proteins regulates transcriptional output of the Hippo pathway. Nat Chem Biol 2016;12:282-9.

Holden JK, Crawford JJ, Noland CL, et al. Small Molecule Dysregulation of TEAD Lipidation Induces a Dominant-Negative Inhibition of Hippo Pathway Signaling. Cell Rep 2020;31:107809.

Chong LW, Tsai CL, Yang KC, et al. Targeting protein palmitoylation decreases palmitateinduced sphere formation of human liver cancer cells. Mol Med Rep 2020;22:939-947.

Tang TT, Konradi AW, Feng Y, et al. Small Molecule Inhibitors of TEAD Auto-palmitoylation Selectively Inhibit Proliferation and Tumor Growth of NF2-deficient Mesothelioma. Mol Cancer Ther 2021;20:986-998.

Conboy CB, Velez-Reyes GL, Tschida BR, et al. R-spondin 2 Drives Liver Tumor Development in a Yes-Associated Protein-Dependent Manner. Hepatol Commun 2019;3:1496-1509.

Zhang S, Zhou D. Role of the transcriptional coactivators YAP/TAZ in liver cancer. Curr Opin Cell Biol 2019;61:64-71.

Kim W, Khan SK, Gvozdenovic-Jeremic J, et al. Hippo signaling interactions with Wnt/beta-catenin and Notch signaling repress liver tumorigenesis. J Clin Invest 2017;127:137-152.

Ye J, Li TS, Xu G, et al. JCAD Promotes Progression of Nonalcoholic Steatohepatitis to Liver Cancer by Inhibiting LATS2 Kinase Activity. Cancer Res 2017;77:5287-5300.

Hyun J, Al Abo M, Dutta RK, et al. Dysregulation of the ESRP2-NF2-YAP/TAZ axis promotes hepatobiliary carcinogenesis in non-alcoholic fatty liver disease. J Hepatol 2021;75:623-633.

Xu MZ, Yao TJ, Lee NP, et al. Yes-associated protein is an independent prognostic marker in hepatocellular carcinoma. Cancer 2009;115:4576-85.

Wang H, Wang J, Zhang S, et al. Distinct and Overlapping Roles of Hippo Effectors YAP and TAZ During Human and Mouse Hepatocarcinogenesis. Cell Mol Gastroenterol Hepatol 2021;11:1095-1117.

Wang X, Zheng Z, Caviglia JM, et al. Hepatocyte TAZ/WWTR1 Promotes Inflammation and Fibrosis in Nonalcoholic Steatohepatitis. Cell Metab 2016;24:848-862.

Chang Y, Liu Q, Zhou Z, et al. Can Statin Treatment Reduce the Risk of Hepatocellular Carcinoma? A Systematic Review and Meta-Analysis. Technol Cancer Res Treat 2020;19:1533033820934881.

Islam MM, Poly TN, Walther BA, et al. Statin Use and the Risk of Hepatocellular Carcinoma: A Meta-Analysis of Observational Studies. Cancers (Basel) 2020;12.
Walker EJ, Ko AH, Holly EA, et al. Statin use and risk of pancreatic cancer: results from a large, clinic-based case-control study. Cancer 2015;121:1287-94.

Tian Y, Yang B, Qiu W, et al. ER-residential Nogo-B accelerates NAFLD-associated HCC mediated by metabolic reprogramming of oxLDL lipophagy. Nat Commun 2019;10:3391.

Yu FX, Zhao B, Panupinthu N, et al. Regulation of the Hippo-YAP pathway by G-protein-coupled receptor signaling. Cell 2012;150:780-91.

Shu Z, Gao Y, Zhang G, et al. A functional interaction between Hippo-YAP signalling and SREBPs mediates hepatic steatosis in diabetic mice. J Cell Mol Med 2019;23:3616-3628.

Sorrentino G, Ruggeri N, Specchia V, et al. Metabolic control of YAP and TAZ by the mevalonate pathway. Nat Cell Biol 2014;16:357-66.

Wang Z, Wu Y, Wang H, et al. Interplay of mevalonate and Hippo pathways regulates RHAMM transcription via YAP to modulate breast cancer cell motility. Proc Natl Acad Sci U S A 2014;111:E89-98.

Hao F, Xu Q, Wang J, et al. Lipophilic statins inhibit YAP nuclear localization, co-activator activity and colony formation in pancreatic cancer cells and prevent the initial stages of pancreatic ductal adenocarcinoma in KrasG12D mice. PLoS One 2019;14:e0216603.

Moon SH, Huang CH, Houlihan SL, et al. p53 Represses the Mevalonate Pathway to Mediate Tumor Suppression. Cell 2019;176:564-580 e19.

Reig M, Forner A, Rimola J, et al. BCLC strategy for prognosis prediction and treatment recommendation: The 2022 update. J Hepatol 2022;76:681-693.

Gao R, Kalathur RKR, Coto-Llerena M, et al. YAP/TAZ and ATF4 drive resistance to Sorafenib in hepatocellular carcinoma by preventing ferroptosis. EMBO Mol Med 2021;13:e14351.

Sun T, Mao W, Peng H, et al. YAP promotes sorafenib resistance in hepatocellular carcinoma by upregulating survivin. Cell Oncol (Dordr) 2021;44:689-699.
