UNIVERSITÄTSKLINIKUM HAMBURG-EPPENDORF

Zentrum für Experimentelle Medizin,
Institut für Biochemie und Signaltransduktion

Direktor: Prof. Dr. med. Georg W. Mayr

Combined targeting of AKT and mTOR synergistically inhibits proliferation of hepatocellular carcinoma cells

Dissertation

zur Erlangung des Grades eines Doktors der Medizin
an der Medizinischen Fakultät der Universität Hamburg

vorgelegt von:
Florian Ewald
aus Bad Meinberg, Nordrhein Westphalen

Hamburg 2012

**Angenommen von der
Medizinischen Fakultät der Universität Hamburg am: 25.06.2013**

**Veröffentlicht mit Genehmigung der
Medizinischen Fakultät der Universität Hamburg.**

Prüfungsausschuss, der/die Vorsitzende: Prof. Dr. Manfred Jücker

Prüfungsausschuss, zweite/r Gutachter/in: Prof. Dr. Udo Schumacher

~~Prüfungsausschuss, dritte/r Gutachter/in:~~

Inhaltsverzeichnis

Inhaltsverzeichnis 3
1 Manuskript 5
2 Abstract 6
3 Keywords 7
4 Background 7
5 Results 8
  5.1. Feedback activation of AKT following mTOR inhibition with RAD001 is concentration- and time-dependent 8
  5.2. Differential and isoform specific activation of AKT1, AKT2 and AKT3 during feedback activation after mTOR inhibition 10
  5.3. Dual targeting of mTOR and AKT highly synergistically inhibits proliferation of HCC cell lines 11
  5.4. Knockdown of a single AKT isoform is synergistic with mTOR inhibition on proliferation of HCC cells 12
  5.5. RAD001 and MK-2206 are highly synergistic in vivo 13
  5.6. All AKT isoforms are activated in a HCC patient with mutated PI3K 13
6 Discussion 14
7 Conclusion 16
8 Methods 17
  8.1. Materials 17
  8.2. Cell culture 17
  8.3. Western Blot analysis 17
  8.4. Lentiviral knockdown of AKT isoforms 17
  8.5. Proliferation and Cell Cycle Assay 18
  8.6. Immunoprecipitation and AKT isoform specific in vitro kinase assay 18
  8.7. Primary human HCC samples 19
  8.8. Mutation analysis of PI3K, AKT and mTOR in HCC samples 19
  8.9. Animal Experiments 19
  8.10. Statistical Analysis 20
  8.11. Abbreviations 20
9 Competing interests 20

10 Authors’ contributions 21
11 Acknowledgements 21
12 Figures 21
13 References 33
14 Tables 38
15 Letter of Acceptance 41
16 Zusammenfassende Darstellung der Publikation 42
  16.1. Einleitung 42
  16.2. Material und Methoden 43
  16.3. Ergebnisse 44
  16.4. Diskussion 46
  16.5. Erklärung des Eigenanteils an der Publikation 48
17 Danksagung 48
18 Lebenslauf 49
19 Eidesstattliche Versicherung 50

1 Manuskript

Combined targeting of AKT and mTOR synergistically inhibits proliferation of hepatocellular carcinoma cells

Nicole Grabinski[1*], Florian Ewald[2*], Bianca T. Hofmann[1#], Katharina Staufer[2§], Udo Schumacher[3], Björn Nashan[2] and Manfred Jücker[1]

[1]Center for Experimental Medicine, Institute of Biochemistry and Signal Transduction, University Medical Center Hamburg-Eppendorf, [2]Department of Hepatobiliary and Transplant Surgery, University Medical Center Hamburg-Eppendorf, Martinistr. 52, 20246 Hamburg, Germany. [3]Center for Experimental Medicine, Department of Anatomy and Experimental Morphology, University Cancer Center, University Medical Center Hamburg-Eppendorf

[§] present address: Department of Internal Medicine III, Division of Gastroenterology and Hepatology, Medical University of Vienna, Vienna, Austria
[#] present address: Department of General, Visceral and Thoracic Surgery, University Medical Center Hamburg-Eppendorf, Hamburg, Germany

[*] N.G. and F.E. contributed equally to this work

Corresponding author: Dr. Manfred Jücker
Center of Experimental Medicine
Institute of Biochemistry and signal Transduction
University Medical Center Hamburg-Eppendorf
Martinistr. 52, 20246 Hamburg, Germany
juecker@uke.uni-hamburg.de

2 Abstract

Background: Due to the frequent dysregulation of the PI3K/AKT/mTOR signaling pathway, mTOR represents a suitable therapeutic target in hepatocellular carcinoma (HCC). However, emerging data from clinical trials of HCC patients indicate that mTOR inhibition by RAD001 (Everolimus) alone has only moderate antitumor efficacy which may be due to the feedback activation of AKT after mTOR inhibition. In this study, we analyzed the effects of dual inhibition of mTOR and AKT on the proliferation of HCC cell lines. In addition, we measured the feedback activation of each of the AKT isoforms after mTOR inhibition in HCC cell lines and their enzymatic activity in primary samples from HCC patients.

Methods: The activation status of specific AKT isoforms in human HCC samples and corresponding healthy liver tissue was analyzed using an AKT isoform specific *in vitro* kinase assay. AKT isoform activation after mTOR inhibition was analyzed in three HCC cell lines (Hep3B, HepG2 and Huh7), and the impact of AKT signaling on proliferation after mTOR inhibition was investigated using the novel AKT inhibitor MK-2206 and AKT isoform specific knockdown cells.

Results: AKT isoforms become differentially activated during feedback activation following RAD001 treatment. The combination of mTOR inhibition and AKT isoform knockdown showed only a weak synergistic effect on proliferation of HCC cell lines. However, the combinatorial treatment with RAD001 and the pan AKT inhibitor MK-2206 resulted in a strong synergism, both *in vitro* and *in vivo*. Moreover, by analyzing primary HCC tissue samples we were able to demonstrate that a hotspot mutation (H1047R) of PI3KCA, the gene encoding the catalytic subunit of PI3K, was associated with increased *in vitro* kinase activity of all AKT isoforms in comparison to healthy liver tissue of the patient.

Conclusion: Our results demonstrate that dual targeting of mTOR and AKT by use of RAD001 and the pan AKT inhibitor MK-2206 does effectively inhibit proliferation of HCC cell lines. These data suggest that combined treatment with RAD001 and MK-2206 may be a promising therapy approach in the treatment of hepatocellular carcinoma.

3 Keywords

Hepatocellular carcinoma, RAD001, MK-2206, proliferation, AKT, AKT isoform kinase assay

4 Background

Hepatocellular carcinoma (HCC) is the third leading cause of cancer mortality worldwide, with an increasing incidence in the United States and Europe [1, 2]. Only 30-40% of patients are amenable to potentially curative therapies, such as surgical resection, because of the often advanced stage of disease at the time of diagnosis. Today, the multi-kinase inhibitor sorafenib is the only systemic therapy to improve survival in these patients [3]. However, prognosis of advanced HCC remains poor, and new effective therapeutic strategies are urgently needed.

The PI3K/AKT/mTOR signaling pathway is a promising target with respect to its frequent dysregulation in hepatocellular carcinoma and its central role in regulating cell proliferation, migration, survival and angiogenesis [4, 5]. Aberrant mTOR signaling has been detected in up to 48% of hepatocellular carcinoma, and a correlation between poor outcome and mTOR signaling activation has been shown [6]. Phosphorylation of AKT at S473 was detected in up to 71% of HCC samples, and associated with invasion, metastasis, and vascularization of HCC [7].

Several inhibitors targeting mTOR are tested in clinical trials at present [8]. Clinical trials revealed that the rapamycin derivative RAD001 (Everolimus) is sufficient to improve the overall survival of patients with metastatic renal carcinoma and subependymal giant cell astrocytoma [9, 10]. Emerging data from clinical trials of HCC patients indicate that RAD001, even well tolerated, has only moderate antitumor efficacy in HCC patients [11, 12]. A negative feedback loop resulting in the activation of AKT following mTOR inhibition has been observed in a variety of cancer cell lines and human tumor samples of colon and breast cancer [13]. Since the antitumor efficacy of rapalogues in patients is modest, activation of AKT as a central regulator of cell growth is a potentially unfavorable event resulting from cancer treatment with mTOR inhibitors [14]. AKT feedback is thought to be mediated by inhibition of p70S6 kinase activity, resulting in an increase in IRS-1 (insulin receptor substrate 1) expression [15]. Since it has been demonstrated that cells lacking IRS-1 also show increased AKT phosphorylation following mTOR inhibition, other mechanisms of feedback activation have been proposed [16]. An increase in the phosphorylation of receptor tyrosine kinases, i.e. EGFR, HER2, HER3 among others, following treatment with rapamycin was demonstrated [17] and may represent an IRS-1-independent way of increased AKT signaling.

The serine/threonine kinase AKT is a key player of the regulatory network of the cell and affects virtually all cellular activities, including growth, survival, movement, differentiation and metabolism [18, 19]. Currently, three mammalian isoforms of AKT (AKT1/PKBα, AKT2/PKBβ, and AKT3/PKBγ) have been identified [20, 21]. The isoforms share a high degree of structural homology with human AKT1 having 81 and 83% amino acid identity with AKT2 and AKT3, respectively. Although there is evidence for partial functional overlap of the AKT isoforms, studies on isoform specific knockout mice revealed their distinct functional roles underlined by diverse signaling cascades, thereby controlling cell growth, metabolism, cell proliferation and survival [22, 23]. Specific functions of each isoform have also been proposed in human carcinoma cell lines and mouse models [24-26].

In this study, we analyzed the AKT feedback activation following RAD001 treatment in three HCC cell lines with different AKT isoform expression levels. For the first time differential changes in AKT isoform activity following RAD001 treatment were documented. Furthermore, the importance of AKT isoform specific signaling following mTOR inhibition has been investigated by combination of the mTOR inhibitor RAD001 either with the new orally active allosteric pan AKT inhibitor MK-2206 [27], or AKT isoform specific knockdown cells. Here, we demonstrate that inhibition of mTOR and AKT in combination acts synergistically on cell proliferation of HCC cells. Our results suggest that dual targeting of mTOR and AKT might be a new promising therapeutic approach in the treatment of hepatocellular carcinoma.

5 Results

5.1 Feedback activation of AKT following mTOR inhibition with RAD001 is concentration- and time-dependent

In order to investigate feedback activation of AKT following mTOR inhibition we analyzed the activation of the PI3K/AKT/mTOR pathway in the three HCC cell lines

Hep3B, HepG2 and Huh7. All HCC cell lines showed a constitutive activation of the PI3K/AKT/mTOR pathway as demonstrated by phosphorylation of AKT (S473 and T308), mTOR (S2448), representing mTORC1 activity [28], and pS6 (S240/S244) which is a downstream substrate of mTORC1 and S6-kinase (Fig. 1A). Treatment of the HCC cell lines with various concentrations of RAD001 resulted in a marked suppression of phosphorylation of mTOR (S2448) and the downstream S6 protein (S240/244) (Fig. 1A). Interestingly, we observed a differential feedback activation of AKT in a concentration-dependent manner after treatment with RAD001 for 24 hours with respect to phosphorylation of AKT at residues S473 versus T308 (1B). The feedback phosphorylation at S473 showed a peak level at 1 nM (Hep3B and Huh7) and only a lower or even no increase at all at higher concentrations of RAD001. In contrast, feedback phosphorylation of T308 was observed at low and high concentrations of RAD001 (Fig. 1A, B).

Because we did not observe an increase in the phosphorylation of AKT at S473 in HCC cells after treatment with a higher concentration of 100 nM RAD001 at 24 hours (Fig. 1B), we performed a more detailed time kinetic from 3 up to 72 hour (Fig. 1C and D, Fig S1). No significant time dependent change in pAKT (S473) expression was observed in Hep3B cells at 100 nM RAD001 (Fig S1). Surprisingly, a short term increase of pAKT (S473) expression was evident in both Huh7 (Fig. 1C) and HepG2 (Fig. 1D) cells with a peak between 3 to 12 h after treatment with RAD001. The basal pAKT (S473) expression level was reestablished after 24 h and no further increase was observed at 48h post-treatment. The decrease of pAKT (S473) represents inhibition of mTORC2 activity [29]. This is in line with previous studies showing suppressed mTORC2 assembly after prolonged incubation of cells with allosteric mTOR inhibitors [30]. In the case that the culture medium was replaced after 48 h with medium containing fresh RAD001, subsequent AKT feedback phosphorylation on S473 was absent or only weakly detectable 3 to 6 h after the addition of new RAD001 (Fig. 1C and D). Conversely, there was a clear time-dependent increase in pAKT (T308), reaching its maximum after >30 h of incubation. While cells treated one time only with RAD001 show elevated levels of pAKT (S473) after 60 and 72 h, no increase of pAKT (S473) expression was observed after 60 and 72 h in cells re-treated with fresh culture medium after 48 h (Fig. 1C and 1D). This late increase in pAKT (S473) might be due to degradation of RAD001 in culture medium, thereby possibly relieving mTORC2 complexes of RAD001-mediated inhibition which was described before [31]. All results were confirmed in at least two independent experiments

5.2 Differential and isoform specific activation of AKT1, AKT2 and AKT3 during feedback activation after mTOR inhibition

The regulation of AKT kinase activity involves phosphorylation of threonine residue 308 in the activation loop and serine residue 473 in the hydrophobic region [32, 33]. Of note, phospho-specific AKT antibodies directed against S473 and T308 used here and in numerous other publications do not discriminate between the different AKT isoforms. Therefore, the representation of single AKT isoform activities measured by the expression of pAKT (S473) or (T308) with phospho-AKT specific antibodies remains unclear. A more detailed insight into the regulation of AKT isoforms may be interesting in the term of developing of AKT isoform specific inhibitors as anticancer drugs. To assess whether a specific AKT isoform becomes predominantly activated after RAD001 treatment, we first analyzed the expression of AKT isoforms in HCC cell lines. As shown in Fig 2A, all cell lines expressed AKT1 and AKT2, with the highest expression levels observed in Huh7 cells (Fig. 2A). In contrast, AKT3 expression was restricted to Hep3B cells.

To reveal changes in AKT activity, an AKT isoform-specific, quantitative *in vitro* kinase assay was performed as described previously [24], using the same cell lysates as shown in Fig. 1A. Since AKT3 was not detectable in HepG2 and Huh7 cells either by western blot or by immunoprecipitation technique using different AKT3 antibodies, we analyzed AKT3 kinase activity only in Hep3B cells. Interestingly, we observed a differential concentration-dependent pattern of AKT-isoform activation following RAD001 treatment for the three HCC cell lines analyzed. Hep3B cells showed a moderate increase in AKT2 activity, but no increase in AKT1 and AKT3 activity (Fig. 2B). The increase in AKT2 activity was only observed at 1nM RAD001 but not at higher concentrations. In contrast, in HepG2 cells we observed an increase in AKT1 activity at all concentrations analyzed, whereas AKT2 kinase activity was decreased in a concentration-dependent manner. In Huh7 cells, RAD001 led to a 40- and 20-fold increase in AKT1 and AKT2 kinase activity after stimulation with 1 nM RAD001, respectively. Interestingly, a similar activation of both AKT isoforms was also observed after stimulation of these cells with the higher concentration of 10 and 100 nM RAD001 (Fig 2B) [34].

5.3 Dual targeting of mTOR and AKT highly synergistically inhibits proliferation of HCC cell lines

We next aimed to investigate the impact of AKT activity after RAD001 treatment. By use of MK-2206, a new highly potent allosteric pan-AKT inhibitor, we analyzed dual targeting of mTOR and AKT on proliferation of HCC cells. As shown in Fig. 3A, AKT inhibitor MK-2206 reduced the phosphorylation of pAKT (S473) and (T308) in all HCC cell lines, with no preference for either phosphorylation site. Concomitant with the reduction in pAKT was a moderate reduction in phosphorylation of GSK3β at S9 and S6 at S235/246, albeit to a varying degree among the analyzed cell lines. To evaluate a potential synergistic effect of combined inhibition of mTOR and AKT, we used the method proposed by Chou and Talalay [35]. HCC cell lines were treated with RAD001, MK-2206, or a combination of both compounds with a fixed ratio of 1:5, over a broad range of clinically relevant concentrations. To exclude effects of plating density on proliferation, we established ideal plating densities for each cell line (Fig. S2). The importance of this step was underlined by a marked reduction of proliferation for cells reaching >80% confluence.

Treatment with RAD001 over 72 h resulted in a significant decrease in proliferation of all cell lines, with HepG2 cells being least, and Huh7 being most sensitive to RAD001 (Fig. 3B). In contrast to Huh7 and Hep3B, HepG2 cells harbor a mutation in n-ras (http://rcgdb.bioinf.uni-sb.de/MutomeWeb) which was discussed to contribute to RAD001 resistance [36]. We observed no significant dose dependent effects of RAD001 on proliferation for the concentrations between 1 nM and 1000 nM with the exception that HepG2 cells showed a non-significant trend towards stronger inhibition at higher concentrations of RAD001.

The anti-proliferative efficacy of AKT inhibitor MK-2206 alone was only weak with IC_{50} values of 3.7 µM, 7.4 µM and 3.1 µM for Hep3B, HepG2 and Huh7, respectively (Fig. S3). However, combining RAD001 and MK-2206 led to a synergistic suppression of proliferation in all three cell lines, with Combination Index (CI) values indicating strong, or very strong synergism especially at moderate and higher concentrations of the two compounds (Fig. 3D, Fig. S4). As shown in Fig. 3E combining RAD001 and MK-2206 resulted in a significantly higher accumulation of cells in G0/G1 phase compared to each compound alone. An increase of cells in subG1 phase was present in all cell lines treated with the combination, indicating the presence of apoptotic cells.

Furthermore, since effects of RAD001 alone on proliferation were not dose dependent, we next tested whether synergistic effects were dependent on higher doses of RAD001. We therefore treated HCC cells with increasing concentrations of RAD001 alone or in combination with a fixed dose of MK-2206. As shown in Fig. 3C, strong synergistic effects of dual mTOR- and AKT-inhibition could already be achieved at doses of RAD001 as low as 1 nM. Interestingly, no RAD001 concentration-dependent differences in the synergistic effect of RAD001 and MK-2206 were observed, although low doses of RAD001, i.e. 1 nM, resulted in the strongest increase in phosphorylation of AKT at S473 (Fig. 1A, B) and AKT isoform activity (Fig. 2B).

5.4 Knockdown of a single AKT isoform is synergistic with mTOR inhibition on proliferation of HCC cells

To analyze the impact of single AKT isoforms on proliferation of HCC cell lines, we generated stable AKT1 and AKT2 knockdown cells for all three HCC cell lines. Since we were unable to detect AKT3 at protein level in HepG2 and Huh7 cells, AKT3 knockdown cells were only established for Hep3B cells (Fig. 4A). Knockdown of AKT isoforms was highly effective, and no significant changes in the expression of the remaining AKT isoforms were detected as shown for Hep3B cells.

Next we compared the effect of MK-2206 and knockdown of single AKT isoforms on activation of AKT and mTOR signaling pathways in HCC cell lines (Fig. 4B for Hep3B cells, Fig S5 for HepG2 and Huh7 cells). Treatment with 1.7 µM MK-2206 completely abolished phosphorylation of AKT and decreased phosphorylation of GSK3β at serine residue 9. Knockdown of AKT2 led to a reduced phosphorylation of AKT at S473 and T308 in all three cell lines, whereas knockdown of AKT1 and AKT3 did not result in reduced levels of phosphorylated AKT (Fig 4B, Fig S5).

To further investigate synergistic effects of combined mTOR and AKT isoform inhibition, AKT isoform knockdown cells were treated with 100 nM RAD001 or DMSO for 24 h. In addition, control cells treated with 1.7 µM MK-2206 alone or in combination with 100 nM of mTOR inhibitor RAD001 were analyzed. As shown in Fig 4C, knockdown of AKT1 led to a significant inhibition of proliferation of all investigated HCC cell lines, with the strongest effect observed in Hep3B cells. While depletion of AKT2 reduced proliferation of both, Hep3B and HepG2 cells, knockdown of AKT3 had no significant effect on proliferation of Hep3B cells. In combination with RAD001 knockdown of AKT1 resulted in a synergistic inhibition of proliferation of all HCC cell lines, whereas knockdown of AKT2 was only synergistic in Huh7 cells. Combining RAD001 with pan AKT inhibitor MK-2206 led to a markedly stronger reduction of cell proliferation than combining RAD001 with knockdown of any single AKT isoform.

5.5 RAD001 and MK-2206 are highly synergistic in vivo

Next, we analyzed the efficacy of dual treatment with RAD001 and MK-2206 in a subcutaneous HCC xenograft mouse model. As seen in Figure 5A, combining RAD001 and MK-2206 significantly prolonged survival of mice compared to placebo or each compound alone. Furthermore, a significant decrease in tumor volume compared to placebo was only observed in mice treated with the combination of RAD001 and MK-2206 (Fig. 5B). Until 15 days post-treatment, no significant difference in mouse weight was observed between the four groups, indicating that the treatment was well tolerated. The decrease in the average weight at day 18 in placebo and MK-2206 treated mice reflects tumor cachexia due to tumor progression (Fig. S6). To confirm specific effects of RAD001 and MK-2206 on PI3K/AKT/mTOR signaling, tumor portions from one randomly chosen mouse per group were subjected to Western blot analysis. As seen in Figure 5C, RAD001 almost completely abolished phosphorylation of S6 at serine residue 240/244. Treatment with RAD001 slightly increased the phosphorylation of AKT at threonine residue 308, whereas treatment with MK-2206 suppressed the phosphorylation of AKT at both serine residue 473 and threonine residue 308.

5.6 All AKT isoforms are activated in a HCC patient with mutated PI3K

In order to identify genetic alterations in the PI3K/AKT/mTOR signaling pathway in liver cancer, genomic DNA from 10 primary tumor samples of HCC patients were analysed by direct sequencing after PCR amplification. Yet, mutations in the regulatory p85α subunit of PI3K, the PH domain of the three AKT isoforms and specific domains of mTOR have not been analysed in HCC. The 47 exons of the sequenced genes PIK3R1 (p85α subunit of PI3K), PIK3CA (catalytic subunit of PI3K)

FRAP1 (mTOR), the three AKT isoforms (AKT1, AKT2, AKT3) and the genetic alterations identified within the 10 HCC samples are summarized in Table 1. No genetic alterations have been identified in *AKT1, AKT2* or *AKT3.* A comparison with the NCBI SNP database revealed that genetic alterations detected in PIK3R1 and mTOR (FRAP1) are SNPs. One somatic mutation was identified in PIK3CA encoding the catalytic subunit of PI3K in tumor sample H292 (exon 20, 3140 a>g; H1047R).

To further gain insight into the state of AKT activation and signaling in HCC in vivo, tumor samples used for sequencing have additionally been analysed on protein level by western blotting (Fig. 6A). As expected, we observed heterogeneous expression profiles of phosphorylated AKT. AKT was activated in two out of ten investigated HCC samples, and functional AKT signaling in these two tumor samples was further confirmed by a concomitant phosphorylation of the AKT downstream substrate GSK3β (S9).

The activation status of AKT isoforms was further analysed by AKT isoform specific *in vitro* kinase assays. As shown in Fig. 6B, AKT isoform expression does not correlate with AKT isoform activity, indicating that AKT isoforms are differentially activated independent of their expression level *in vivo*. Furthermore, we demonstrated for the first time that the H1047R mutant in the catalytic subunit of PI3K led to elevated activity of all AKT isoforms in comparison to healthy liver tissue of the patient (see patient H292, Table 1). These results indicate that all AKT isoforms become activated by the oncogenic hot spot H1047R mutant of PI3K in HCC.

6 Discussion

In this study, we aimed to investigate the PI3K/AKT/mTOR signaling pathway in hepatocellular carcinoma by highlighting the feedback activation of AKT and its distinct isoforms following mTOR inhibition by RAD001. Further, we analyzed the activation status of specific AKT isoforms in HCC samples and corresponding healthy liver tissue as well as their diverse implications in terms of proliferation of HCC cell lines. In order to draw a light on genetic alterations of PI3K/AKT/mTOR signaling in hepatocellular carcinoma, DNA sequencing of human tumor samples were performed. The molecular events leading to activation of the PI3K/AKT/mTOR signaling cascade are not fully understood. In general, mutations in mTOR are rare.

Two single amino acid substitutions in TOR1 (FRB domain) have been identified in yeast, exhibiting resistance to caffeine [37]. In addition, a point mutation in TOR2 (FRB domain) was found leading to a weak rapamycin resistance [38]. On humans, two oncogenic mutations of mTOR have been reported so far in colorectal and renal carcinoma [39, 40]. Genetic aberrations in AKT itself have not yet been identified in HCC patients. In contrast, mutations in *PIK3CA*, the gene encoding for the catalytic subunit of PI3K, have been described in up to 35% of patients with HCC [41-43]. Our mutational analysis of ten human HCCs revealed no genetic alteration in mTOR or in any of the AKT isoforms. One somatic “hot spot” mutation of PI3K was detected in the gene *PIK3CA* (exon 20, 3140 a > g [H1047R]). Moreover, we analyzed the expression and activity of AKT isoforms in these tumor samples. Although all AKT isoforms were expressed in HCC samples, results revealed that AKT activity is often confined to particular AKT isoforms and independent of AKT isoform expression. In this study, we demonstrate for the first time that the oncogenic and well characterized H1047R mutant of PIK3CA, leading to constitutive activation of PI3K [44], results in elevated activity of all three AKT isoforms in comparison to healthy liver tissue of this patient. These data indicate that all AKT isoforms become activated by mutant PI3K (H1047R) in HCC. Whether all AKT isoforms are involved in the oncogenic signalling has to be shown in further experiments.

Our data further demonstrate that combining mTOR inhibitor RAD001 and AKT inhibitor MK-2206 shows a strong synergistic effect on the proliferation of HCC cell *in vitro* and *in vivo*. Therefore, dual targeting of AKT and mTOR might be a promising treatment option for HCC patients. Moreover, we give new insight into AKT isoform specific kinase activity and signaling after mTOR inhibition in HCC cells. Increased AKT1 kinase activity following mTOR treatment was reported before in HeLa cells [30]. However, AKT2 and AKT3 kinase activity has not been investigated. Our data demonstrate that single AKT isoforms can be differentially regulated after mTOR inhibition, as shown for HepG2 cells. Therefore, analysis of all AKT isoforms is necessary to understand the complex mechanism of AKT signaling. Overall, we demonstrated that a high expression level of phosphorylated AKT induced by feedback activation following mTOR inhibition can actually represent increased kinase activity of different AKT isoforms. The clinical relevance of this finding is underscored by the fact that increased AKT phosphorylation was recently observed in a significant proportion of tumor samples obtained from patients treated with RAD001 [45]. Which AKT isoforms become activated in patients treated with RAD001 has to be analyzed in further experiments.

In this study, we showed that knockdown of a single AKT isoform had only a minor effect on proliferation of HCC cells, with the most dominant effect observed for AKT1 in Hep3B cells. Although specific functions of AKT isoforms have clearly been demonstrated [26, 46], compensation and redundancy among AKT isoforms might limit the efficacy of AKT isoform specific inhibitors. However, further research is necessary to understand the exact effect of single AKT isoform inhibition on function and activity of remaining AKT isoforms.

Functional analysis of AKT isoforms of different tumor entities revealed specific oncogenic functions for distinct AKT isoforms [47]. Conclusively, the group of Muller demonstrated that AKT1 induced tumor growth, while AKT2 promotes metastasis of ErbB2-induced breast cancer *in vivo* [48]. Taking together these results suggest that cancer patients would profit more of a pan AKT inhibitor than of AKT isoform specific inhibitors. Consequently, inhibition of mTOR by RAD001 in combination with knockdown of a single AKT isoform evoked only small synergistic effects on proliferation of HCC cells and was additionally not restricted to a single AKT isoform as shown for Huh7 cells. In order to investigate dual targeting of mTOR and total AKT, we analyzed the efficacy of combination of mTOR inhibitor RAD001 with the potent pan AKT inhibitor MK-2206. In contrast to single AKT isoform knockdowns, treatment with pan AKT inhibitor MK-2206 in combination with RAD001 led to a significant, highly synergistic reduction of cell proliferation of all HCC cell lines tested. These data suggest that the inhibition of all AKT isoforms using a pan AKT inhibitor like MK-2206 is necessary to achieve profound synergistic effects in combination with the mTOR inhibitor RAD001. Highlighting the dual targeting of mTOR and AKT as an efficient therapy approach of HCC is of great clinical interest, since MK-2206 is already being tested in clinical trials and reported to be well tolerated [49, 50].

7 Conclusion

In summary, our data demonstrate that dual targeting of mTOR and AKT led to synergistic inhibition of proliferation of HCC cell lines. Further, our results suggest that inhibition of all, rather than one specific AKT isoform is necessary to achieve bold synergistic effects on cell proliferation. In conclusion, the combination of mTOR inhibitor RAD001 and pan AKT inhibitor MK-2206 might represent a new promising treatment strategy for patients with advanced HCC.

8 Methods

8.1 Materials

RAD001 was provided by Novartis (Basel, Switzerland). MK-2206 was obtained from Selleck Chemicals (Houston, TX, USA). Stock solutions with a concentration of 10 mM were prepared and stored at -80 °C. All RAD001 solutions were thawed and refrozen for a maximum of three times and then discarded. Antibodies against pan AKT, AKT1, AKT2, pAKT (S473), pAKT (T308), mTOR, pmTOR (S2448), pmTOR (S2481), Raptor, Rictor, pERK (T202/204), ERK, pS6 (S240/244), IRS-1 and pIRS-1 (S636/639) were purchased from Cell Signaling Technology (Danvers, MA). Antibodies against AKT2 and HSC-70 were purchased from Santa Cruz. AKT3 antibody was obtained from Millipore (Schwallbach, Germany). 7-AAD was obtained from BD Biosciences (Pharmingen, CA, USA).

8.2 Cell culture

The three hepatocellular carcinoma cell lines Hep3B, HepG2 and Huh-7 were a kind gift from Prof. Dr. H. Will at the Heinrich Pette Institute, Hamburg, Germany. All cell lines were maintained in DMEM, supplemented with 10% (v/v) FCS, and 1% (v/v) penicillin and streptomycin. Cells were cultured at 37 °C in a humidified atmosphere containing 5% CO_2. All cells were tested for mycoplasma contamination every 2-3 months.

8.3 Western Blot analysis

Western blot analysis was performed as described previously [24]. Protein expression was quantified using an LAS-3000 Imager from Fuji (Raytest, Straubenhardt, Germany).

8.4 Lentiviral knockdown of AKT isoforms

pLKO.1-puro vector encoding either AKT1, AKT2, AKT3 or scrambled shRNA were purchased from Sigma-Aldrich (Taufkirchen, Germany). Generation of pseudotype lentiviruses and transduction were performed as previously described [24]. Transduced cells were selected by addition of puromycin (Sigma-Aldrich, Taufkirchen, Germany) to culture medium (final concentration 1.5 µg/ml) for at least two weeks before experiments were carried out.

8.5 Proliferation and Cell Cycle Assay

Proliferation was analyzed either by flow cytometry using the BrdU APC Flow Kit (BD, Pharmingen, CA, USA) or with the colorimetric BrdU ELISA Kit (Roche®, Basel, CH) as indicated in the figure legends. For FACS-based assays, cells were seeded into 10cm dishes and allowed to attach overnight. Then, medium was replaced by medium containing RAD001, MK-2206, a combination of both, or DMSO as control. Final DMSO concentration in culture medium was 0.1% (v/v) in all experiments. For labeling BrdU (final concentration 10 µM) was added and cells were incubated for 12 to 16 h. For cell cycle analysis, cells were fixed in ice cold 70% ethanol for at least 6 h, washed and subsequently incubated with 5 µg 7-AAD and 5 µg RNAse A for one hour. Each experiment was performed in triplicates and has been repeated at least one time. Analysis was performed on BD Canto II flow cytometer (BD Pharmingen, CA, USA). Cell cycle analysis was performed using FlowJo 7.6.5 software.

For BrdU ELISA assays, cells were seeded into 96-well plates and allowed to attach overnight. Cells were then incubated for 72 h with different concentrations of MK-2206, RAD001, or a combination of both. Controls were treated with DMSO only. BrdU ELISA was performed as described by the manufacturer (Becton Dickenson, Heidelberg, Germany). Each experiment was repeated at least three times in quadruplicates.

8.6 Immunoprecipitation and AKT isoform specific in vitro kinase assay

Immunoprecipitation of AKT isoforms and subsequent *in vitro* kinase assay was performed as described before [24]. Whole samples were analyzed by western blot technique probed with pGSK3α/ß (S9/21) and panAKT antibody. Subsequently, nitrocellulose membrane was incubated with secondary goat anti-mouse antibody (Santa Cruz Biotechnology, CA, USA) to detect mouse IgG levels for sample correction.

8.7 Primary human HCC samples

The human investigations were performed according to the Declaration of Helsinki after approval was obtained by the local ethics committee of the Medical Association Hamburg. From all patients, written informed consent was obtained prior to study related procedures. Tumor samples and samples of corresponding healthy liver tissue of HCC patients treated at the University Medical Center Hamburg Eppendorf, Department of Hepatobiliary and Transplant Surgery were stored at Indivumed (Hamburg, Germany) following the Indivumed Standard of Biobanking (http://www.indivumed.com). Genomic DNA isolation and sequence analysis was performed by Inostics (Hamburg, Germany). For protein analysis and kinase assays tissue samples were lysed by homogenisation of samples with Lysis Matrix-D (MP, USA) in NP-40 lysis buffer (containing: 50 mM HEPES pH 7.5, 150 mM NaCl, 1% NP-40, 2% aprotinin, 2 mM EDTA, 50 mM NaF, 10 mM NaPPi, 10% glycin, 1 mM vanadate and 1 mM PMSF) with the tissue lyser MX Pro (MP, USA).

8.8 Mutation analysis of PI3K, AKT and mTOR in HCC samples

Sequence analysis of genes from 10 HCC samples encoding the p85α adapter subunit of PI3K (exon 9-17 of PIK3RI), the p110α catalytic subunit of PI3Kα (exon 2 and 10-21 of PIK3CA), mTOR (exon 44-57 of FRAP1), AKT1 (exon 3-6), AKT2 (exon 2-5) or AKT3 (exon 1-3) were performed by amplification of the exons with primers located in the neighboring introns by PCR and sequenced using BigDye Terminator 3.1 according to the instructions by the manufacturer (Applied Biosystems). Primer sequences can be found in Table S1.

8.9 Animal Experiments

All experimental protocols were approved by local authorities (Ministry of Health and Consumer Protection, Hamburg, Germany, Permit Number G52/11). 2x10^6 Huh7 cells were injected subcutaneously into SCID mice (female, age 8 weeks, n=7 per group, obtained from Charles River, Sulzfeld, Germany). Upon establishment of palpable tumours after three weeks, mice were randomly assigned to one of the four groups (Placebo, RAD001, MK-2206, or RAD001 and MK-2206), and treatment was started. Tumor growth was monitored by regular visual inspection and tumor dimensions were measured every 2-3 days. Tumor volume was calculated using the formula longest tumor diameter x (shortest tumor diameter)^2 / 2. RAD001, formulated as a microemulsion, was dosed at 1 mg/kg body weight and administered daily Monday through Friday. MK-2206 was formulated in a 30% (w/v) Captisol solution and administered Monday, Wednesday and Friday dosed at 100 mg/kg. A placebo microemulsion (provided by Novartis) and a 30% (w/v) Captisol solution served as placebo. The compounds were mixed immediately before administered by gavage in a total volume of 100 µl. Animals were treated until termination criteria (tumor ulceration, tumor size > 2 cm in largest diameter, loss of body weight exceeding 20 %) were met, or for a maximum of 22 days when all mice in the placebo group had to be withdrawn. Xenograft primary tumours were harvested at necropsy and a portion of each tumor was snap frozen on liquid nitrogen for Western Blot analysis.

8.10 Statistical Analysis

Student's t-Test (unpaired, 2-tailed) was calculated based on the data of at least three independent experiments. Bonferroni correction for multiple testing was performed where applicable. Results were considered significant if $p<0.05$. All error bars represent SD. Drug interactions were analyzed based on the median effect method of Chou and Talalay [35]. CalcuSyn software (Biosoft, Cambridge, UK) was used to calculate the combination index (CI). CI values from 0.3 to 0.7 are considered to indicate synergism, CI values below 0.3 are considered to represent strong synergism, and values below 0.1 very strong synergism. IC_{50} values were calculated using CurveExpert Professional 1.3 software. Chi-squared test was used to test for significant differences in mouse survival.

8.11 Abbreviations

mTOR: mammalian target of rapamycin; PI3K: phosphatidylinositol 3-kinase; PI3KCA: catalytic subunit of phosphatidylinositol 3-kinase; IRS-1: insulin receptor substrate 1; BrdU: 5-bromo-2'-deoxyuridine; DMSO: dimethyl sulfoxide; PBS: phosphate buffered saline; HCC: hepatocellular carcinoma, CI: combination index.

9 Competing interests

This study was funded by a research grant from Novartis Pharma GmbH.

10 Authors' contributions

NG, FE, BH, KS, US, BN and MJ designed the study. FE, NG and MJ performed the experiments and interpreted the experimental findings. FE and NG drafted the manuscript. FE, NG and MJ wrote the final version of the manuscript. All authors read and approved the final manuscript.

11 Acknowledgements

We would like to thank Prof. Dr. H. Will of the Heinrich Pette Institute, Hamburg, for providing the HCC cell lines, Dr. Kerstin David from Indivumed Hamburg for providing primary HCC samples and Dr. Frank Diehl from Inostics Hamburg for sequence analysis of primary HCC samples. We are grateful to Susanne Feldhaus and Tobias Gosau for technical assistance. Florian Ewald is a fellow of the University Cancer Center Hamburg (UCCH). Udo Schumacher is grateful for the support from the Mildred Scheel Stiftung for the animal core facility.

12 Figures

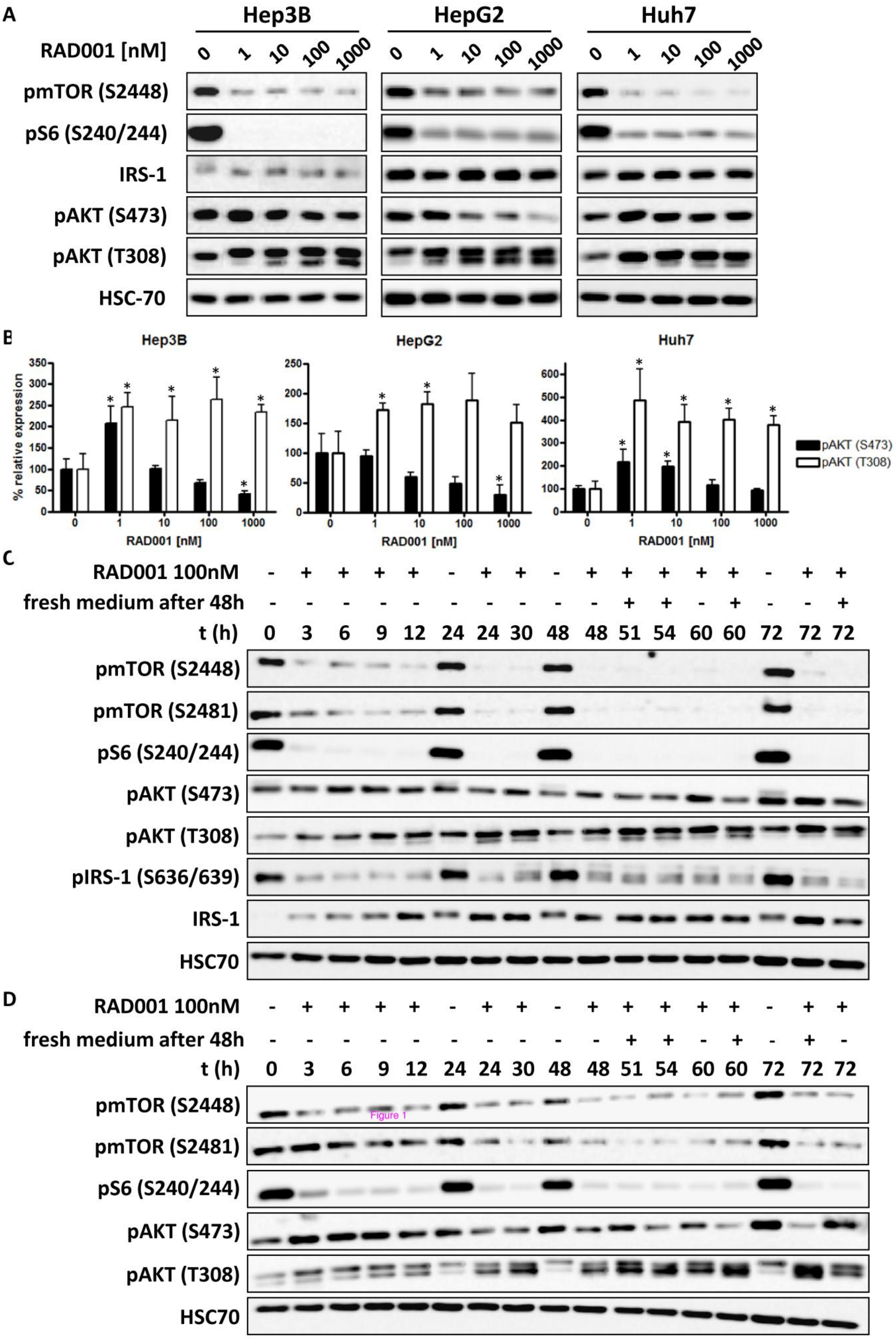
A
Hep3B
HepG2
Huh7
RAD001 [nM]
0
1
10
100
1000
pmTOR (S2448)
pS6 (S240/244)
IRS-1
pAKT (S473)
pAKT (T308)
HSC-70
B
Hep3B
HepG2
Huh7
% relative expression
RAD001 [nM]
pAKT (S473)
pAKT (T308)
C
RAD001 100nM
fresh medium after 48h
t (h)
0 3 6 9 12 24 24 30 48 48 51 54 60 60 72 72 72
pmTOR (S2448)
pmTOR (S2481)
pS6 (S240/244)
pAKT (S473)
pAKT (T308)
pIRS-1 (S636/639)
IRS-1
HSC70
D
RAD001 100nM
fresh medium after 48h
t (h)
0 3 6 9 12 24 24 30 48 48 51 54 60 60 72 72 72
pmTOR (S2448)
pmTOR (S2481)
pS6 (S240/244)
pAKT (S473)
pAKT (T308)
HSC70

Figure 1

Figure 1, Feedback activation of AKT after mTOR inhibition is time- and dose dependent

(A) HCC cell lines Hep3B, HepG2 and Huh7 were treated for 24 h with increasing concentrations of RAD001 as indicated. Phosphorylation status of mTOR and AKT was analyzed by Western blot with phospho specific antibodies. (B) Dose dependent expression of pAKT (S473) and pAKT (T308) after 24 h treatment with RAD001 was quantified from three independent experiments as shown in A. Columns, mean percentage of three independent experiments; bars, SD, * p<0.05. (C) Huh7 and (D) HepG2 cells were treated with 100 nM RAD001 up to 72 h, and cell lysates were prepared at the indicated time points. Where indicated, medium was removed after 48h and replaced by fresh, 100 nM RAD001 containing medium. HSC70 served as loading control.

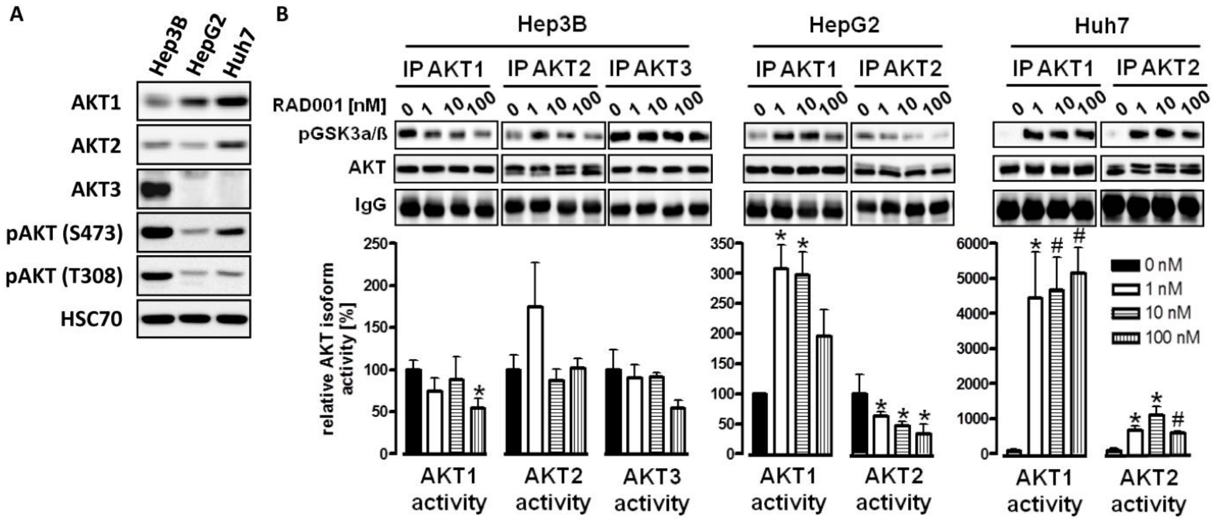

Figure 2, Differential and isoform specific activation of AKT1, AKT2 and AKT3

(A) Comparison of AKT isoform expression in HCC cell lines. Exponentially growing cells were seeded into 10cm dishes and allowed to attach for 24 h. Cells were then lysed and analyzed by Western blot. One representative experiment out of three is shown. (B) HCC cells were treated over 24 h with the indicated concentration of RAD001. AKT isoform specific *in vitro* kinase assays were performed following quantitative AKT isoform immunoprecipitation, based on the same cell lysates as shown in Figure 1A and B. GSK3α/β fusion protein was used as an AKT substrate and phosphorylation at (S9/21) detected by Western blot. Columns, mean of three independent experiments; bars, SD. * p< 0,05; # p< 0,01.

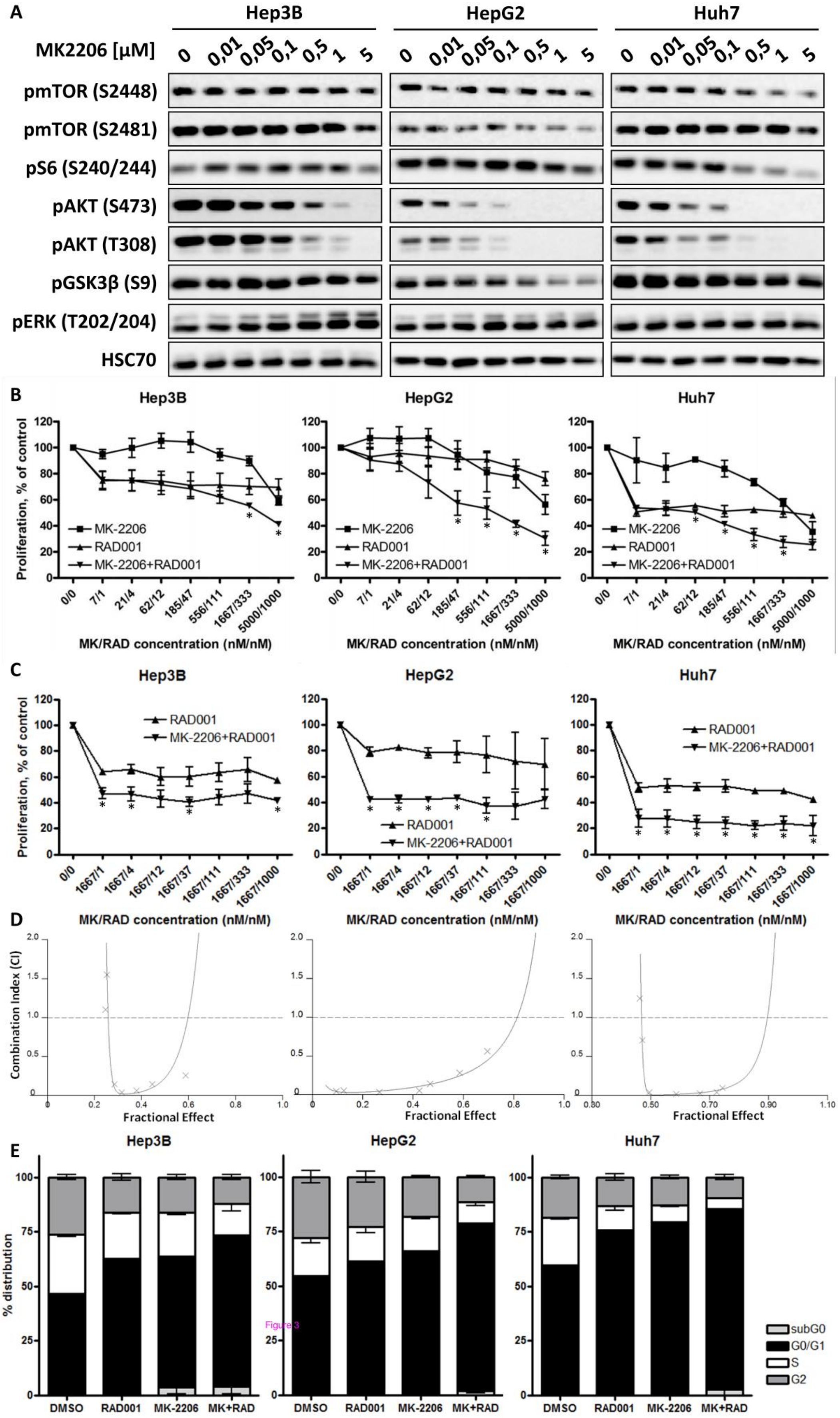
A
Hep3B
HepG2
Huh7
MK2206 [µM]
0 0,01 0,05 0,1 0,5 1 5
pmTOR (S2448)
pmTOR (S2481)
pS6 (S240/244)
pAKT (S473)
pAKT (T308)
pGSK3β (S9)
pERK (T202/204)
HSC70
B
Proliferation, % of control
MK-2206
RAD001
MK-2206+RAD001
0/0 7/1 21/4 62/12 185/47 556/111 1667/333 5000/1000
MK/RAD concentration (nM/nM)
C
0/0 1667/1 1667/4 1667/12 1667/37 1667/111 1667/333 1667/1000
D
Combination Index (CI)
Fractional Effect
E
% distribution
DMSO
RAD001
MK-2206
MK+RAD
subG0
G0/G1
S
G2
Figure 3

Figure 3, Combining RAD001 with MK-2206 synergistically suppresses proliferation of HCC cell lines

(A) HCC cell lines were treated with the indicated concentration of MK-2206 over 24 h, and changes in mTOR- and AKT-signaling were analyzed by Western Blot. HSC70 served as loading control. (B) HCC cells were seeded into 96 well plates and incubated with increasing concentrations of either RAD001 (triangle), MK2206 (box), or a combination (inverted triangle) of both with a fixed ratio of 1:5. Controls were treated with DMSO only. Proliferation was analyzed after 72 h BrdU-incorporation. Asterisks indicate a significantly stronger inhibition of the drug combination compared to each compound alone, * $p<0.05$. (C) HCC cell lines were treated with RAD001 (triangle) or a combination of RAD001 and MK-2206 (inverted triangle) with a constant concentration of 1.7 µM MK2206 for 72 h. Cells treated with DMSO only served as control. Proliferation was analyzed as in (B). Each data point represents mean of at least three independent experiments, normalized to controls; bars, SD. Asterisks indicate a significantly stronger inhibition of the drug combination compared to each compound alone, * $p<0.05$. (D) Fractional effect plot for the effect of RAD001 and MK2206 as seen in (B). (E) Cell cycle analysis of HCC cell lines after 24 h treatment with 100 nM RAD001, 1.7 µM MK-2206, or the combination of both, compared to DMSO treated controls. Colums: mean of one representative experiment, performed in triplicates; bars: SD. The drug combination resulted in a significant increase of cells in G0/G1 phase compared to each drug alone and compared to controls in all three cell lines ($p<0.05$).

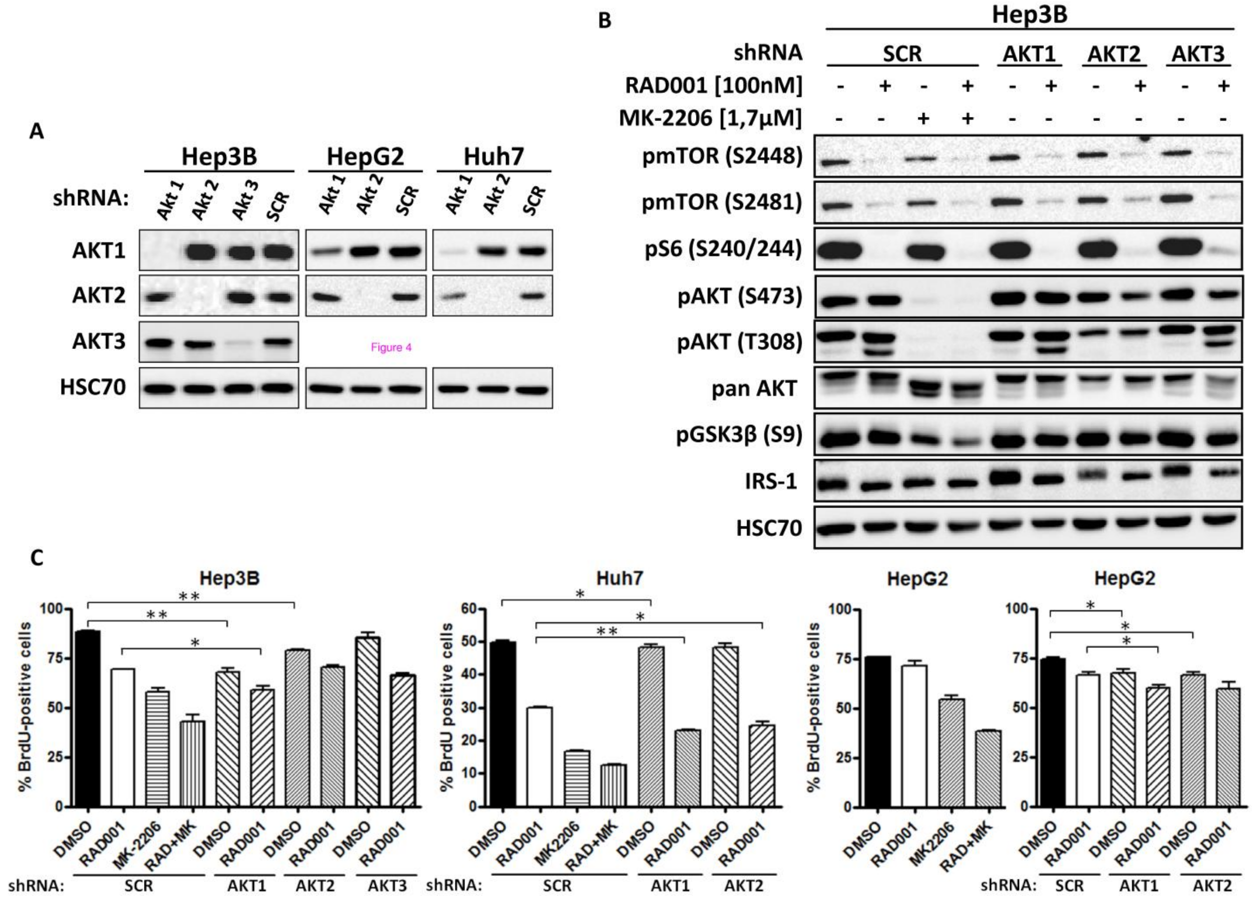

Figure 4, Knockdown of AKT isoforms and mTOR inhibition synergistically inhibits HCC cell proliferation

(A) shRNA mediated knockdown of single AKT isoform in HCC cell lines, confirmed by Western blot. (B) Hep3B knockdown cells were treated with 100 nM RAD001, 1.7 µM MK-2206, the combination of both, or DMSO as control, over 24 h, and mTOR and AKT signaling pathway activity was analyzed by Western blot. HSC70 served as loading control. AKT isoform knockdown cells were treated with 100nM RAD001 over 24 h. (C) Cells transduced with non-target vector were also treated with 1.7 µM MK-2206 or a combination of 100 nM RAD001 and 1.7 µM MK-2206. Proliferation was analyzed by BrdU incorporation. Columns, mean of one experiment performed in triplicates, bars, SD. *, $p < 0.01$; **, $p < 0.001$.

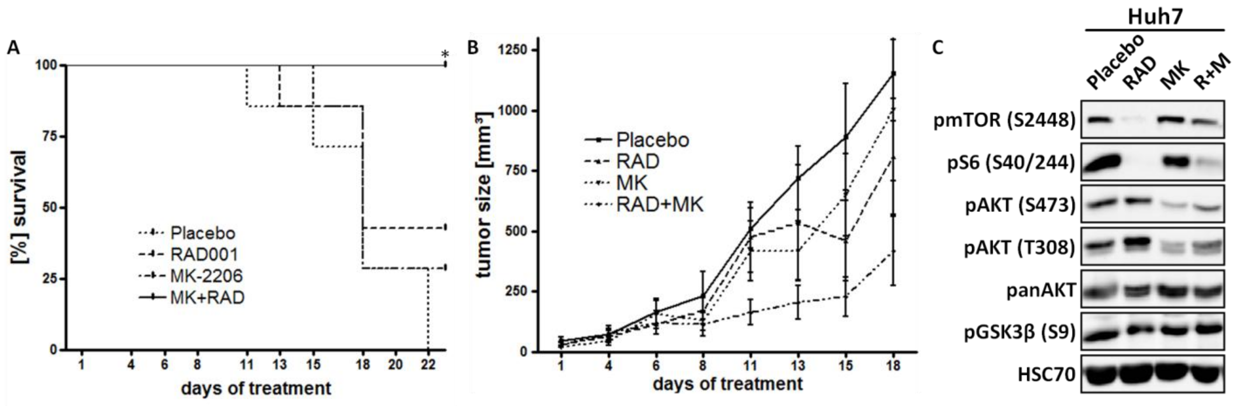

Figure 5, RAD001 and MK-2206 synergistically suppress subcutaneous tumor growth in vivo

Huh7 cells were injected subcutaneously into SCID mice (n=7 per group). After formation of palpable tumors, mice were treated with Placebo, RAD001, MK-2206 or the combination of both, respectively. (A) Treatment with RAD001 and MK-2206 significantly prolonged survival of tumor bearing mice compared to all other groups ($p < 0.05$). (B) Tumor volume was monitored over an 18 day period, presented as mean ± SEM. RAD+MK vs Placebo and RAD+MK vs MK-2206 alone was significant at day 15 ($p<0.05$). Note that one mouse had to be withdrawn from the experiment in the RAD001 and MK-2206 treatment group at day 13 and 15 respectively, and two mice were withdrawn from the Placebo group at days 11 and 15. (C) AKT and mTOR signaling in tumor samples was analyzed by Western blot.

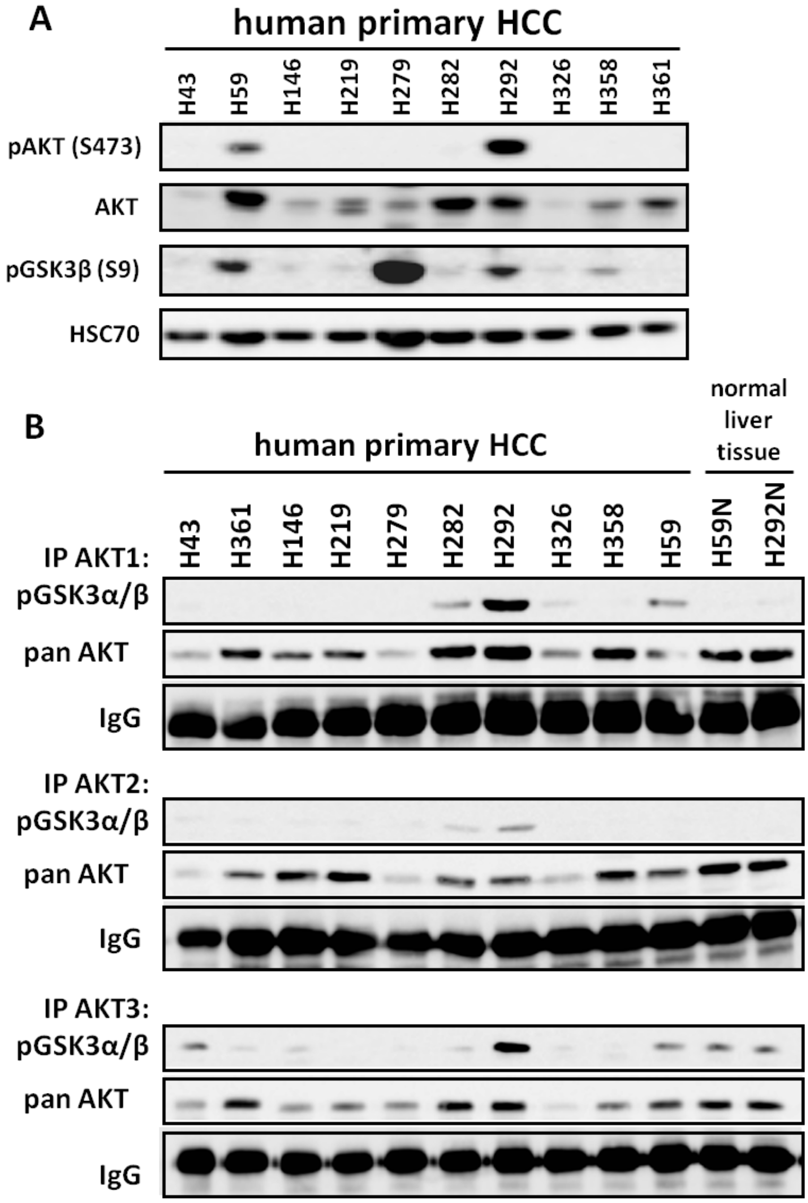

Figure 6, AKT isoforms are differentially activated in human HCC tissue samples

(A) Ten human HCC tissue samples obtained from specimen removed during surgery were analyzed by Western blot for expression of mTOR and AKT signaling proteins. HSC70 served as loading control. (B) Same samples, including two corresponding controls from surrounding normal liver tissue, were analyzed by AKT isoform specific *in vitro* kinase assay as described before. IgG served as loading control.

Fig. S1

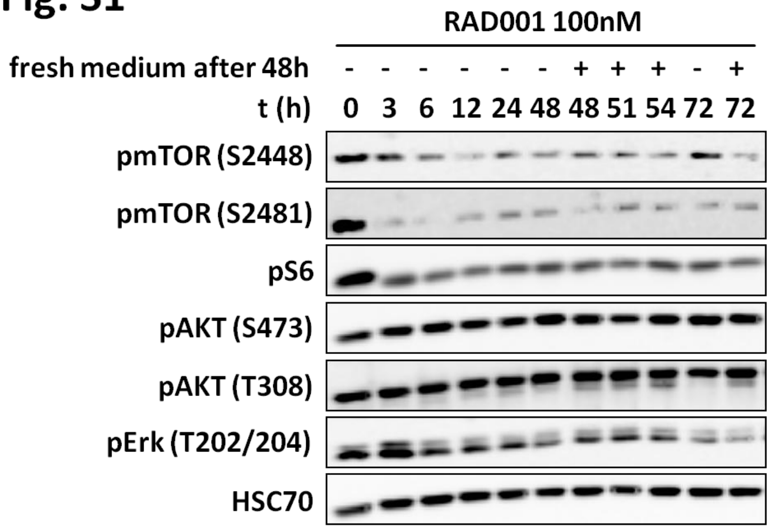

Figure S1, No increase in AKT phosphorylated at T308 or S473 is detectable in Hep3B cells after RAD001 treatment

Hep3B cells were treated with 100 nM RAD001 up to 72 h, and cell lysates were prepared at the indicated time points. Where indicated, medium was removed after 48 h and replaced by fresh, 100 nM RAD001 containing medium. Cell lysates were analyzed for AKT and mTOR signaling. HSC70 was used as loading control.

Fig. S2

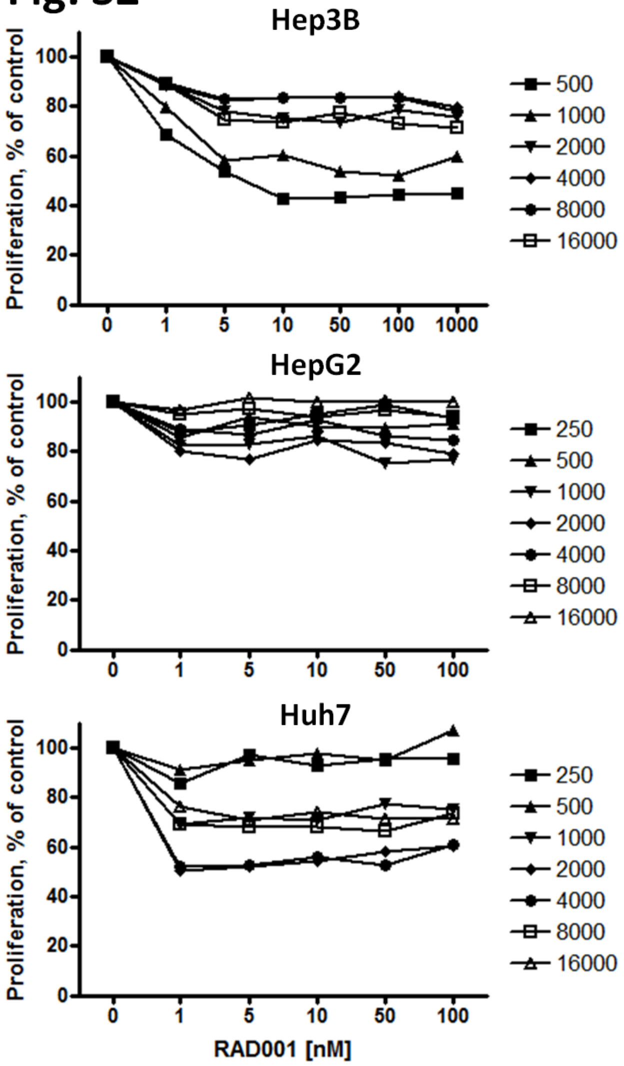

Figure S2, Influence of plating density on proliferation of HCC cell lines

Increasing numbers of HCC cells were seeded into 96-wells and incubated with different concentrations of RAD001 for 72 h. Proliferation was subsequently analyzed by BrdU incorporation. One representative experiment out of two is shown.

Fig. S3

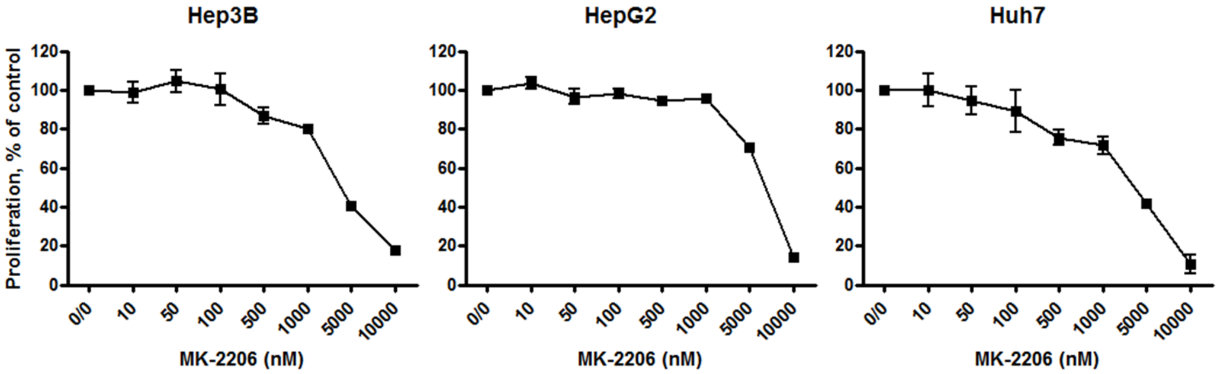

Figure S3, Determination of IC_{50} for MK-2206 in HCC cell lines

HCC cells were seeded into 96 well plates and incubated with increasing concentrations of MK-2206, controls were treated with DMSO only. Proliferation was analyzed after 72 h by detection of BrdU incorporation. Columns: mean of three independent experiments; bars: SD.

Fig. S4

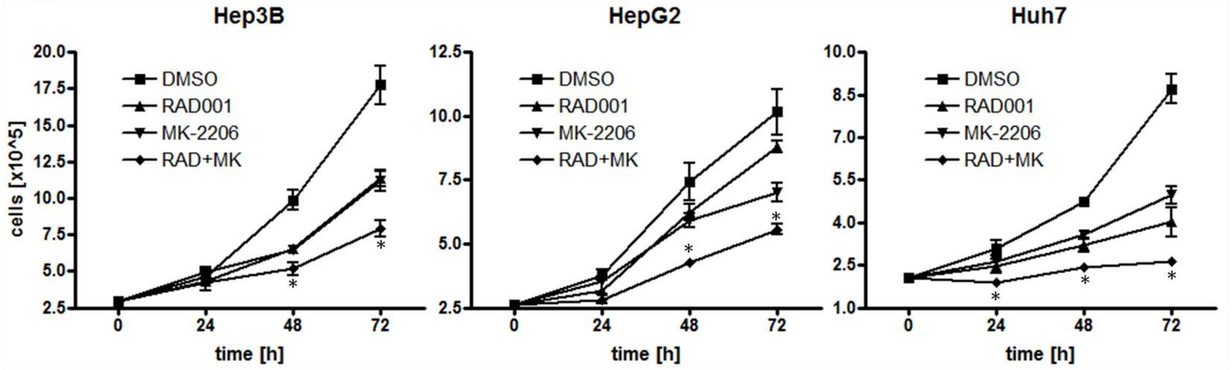

Figure S4, Effect of RAD001 alone or in combination with MK-2206 on HCC cell proliferation

HCC cells (2,5E5 cells for Hep3B and HepG2, 2E5 cell for Huh7) were treated with DMSO, 100 nM RAD001, 1.7 µM MK-2206, or the combination of both. The numbers of viable cells were counted using a Neubauer counting chamber and Trypane blue exclusion after 24, 48 and 72 h treatment. The combination of both compounds inhibits cell proliferation significantly stronger than placebo or each drug alone. * $p< 0.05$.

Fig. S5

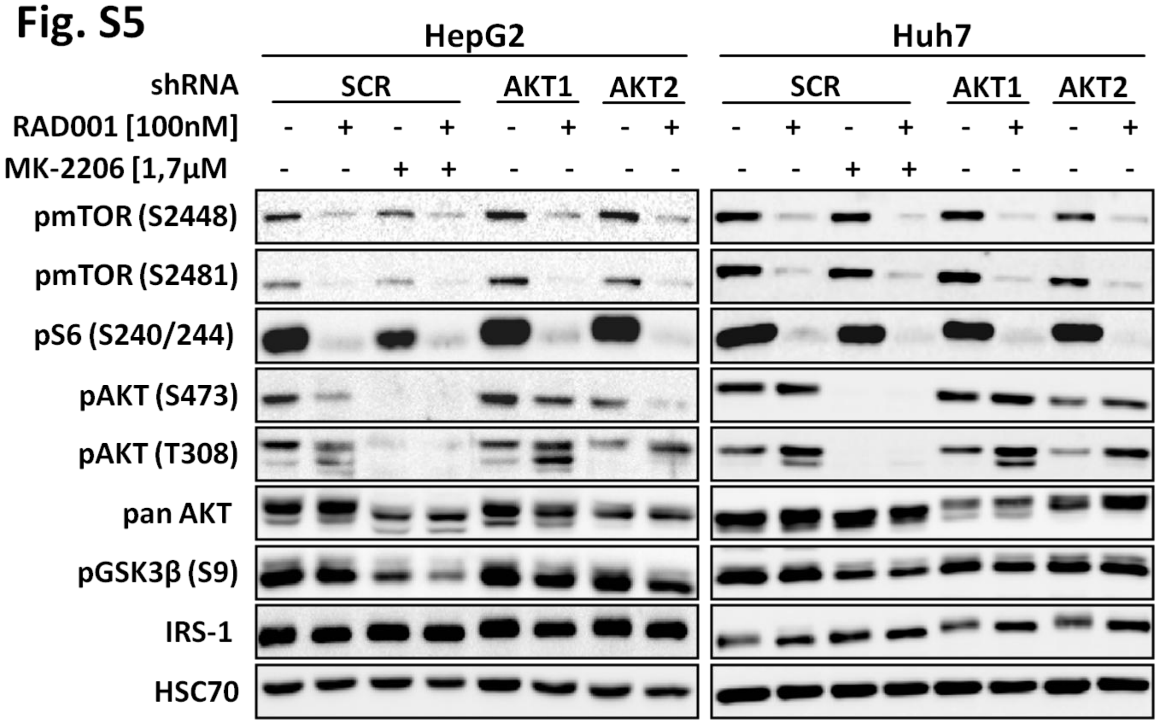

Figure S5, Effect of single AKT isoform knockdown of AKT and mTOR signaling

HepG2 and Huh7 AKT isoform knockdown cells were treated with 100 nM RAD001, 1.7 µM MK-2206, the combination of both, or DMSO, over 24 h, and mTOR and AKT signaling pathway activity was analyzed by Western blot. HSC70 served as loading control.

Fig. S6

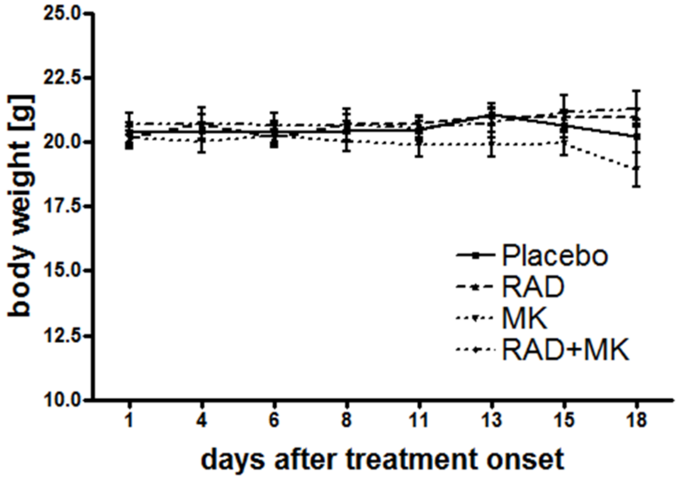

Figure S6, Treatment of mice bearing subcutaneous HCC-tumors had no effect on body weight

Mice treated with Placebo, RAD001, MK-2206 or both compounds in combination were weighed every other day during the first 18 day treatment period. Until day 15, no statistically significant changes in body weight were detected. Weight loss at day 18 in MK-2206 and Placebo treated animals was due to tumor cachexia, and these animals had to be withdrawn from the experiment. Data are presented as mean ± SEM.

13 References

1. Parkin DM, Bray F, Ferlay J, Pisani P: **Estimating the world cancer burden: Globocan 2000.** *Int J Cancer* 2001, **94:**153-156.
2. Altekruse SF, McGlynn KA, Reichman ME: **Hepatocellular carcinoma incidence, mortality, and survival trends in the United States from 1975 to 2005.** *J Clin Oncol* 2009, **27:**1485-1491.
3. Llovet JM, Ricci S, Mazzaferro V, Hilgard P, Gane E, Blanc JF, de Oliveira AC, Santoro A, Raoul JL, Forner A, et al: **Sorafenib in advanced hepatocellular carcinoma.** *N Engl J Med* 2008, **359:**378-390.
4. Bhaskar PT, Hay N: **The two TORCs and Akt.** *Dev Cell* 2007, **12:**487-502.
5. Engelman JA: **Targeting PI3K signalling in cancer: opportunities, challenges and limitations.** *Nat Rev Cancer* 2009, **9:**550-562.
6. Villanueva A, Chiang DY, Newell P, Peix J, Thung S, Alsinet C, Tovar V, Roayaie S, Minguez B, Sole M, et al: **Pivotal role of mTOR signaling in hepatocellular carcinoma.** *Gastroenterology* 2008, **135:**1972-1983, 1983 e1971-1911.
7. Chen JS, Wang Q, Fu XH, Huang XH, Chen XL, Cao LQ, Chen LZ, Tan HX, Li W, Bi J, Zhang LJ: **Involvement of PI3K/PTEN/AKT/mTOR pathway in invasion and metastasis in hepatocellular carcinoma: Association with MMP-9.** *Hepatol Res* 2009, **39:**177-186.
8. Meric-Bernstam F, Gonzalez-Angulo AM: **Targeting the mTOR signaling network for cancer therapy.** *J Clin Oncol* 2009, **27:**2278-2287.
9. Krueger DA, Care MM, Holland K, Agricola K, Tudor C, Mangeshkar P, Wilson KA, Byars A, Sahmoud T, Franz DN: **Everolimus for subependymal giant-cell astrocytomas in tuberous sclerosis.** *N Engl J Med*, **363:**1801-1811.

10. Motzer RJ, Escudier B, Oudard S, Hutson TE, Porta C, Bracarda S, Grunwald V, Thompson JA, Figlin RA, Hollaender N, et al: **Efficacy of everolimus in advanced renal cell carcinoma: a double-blind, randomised, placebo-controlled phase III trial.** *Lancet* 2008, **372:**449-456.
11. Zhu AX, Abrams TA, Miksad R, Blaszkowsky LS, Meyerhardt JA, Zheng H, Muzikansky A, Clark JW, Kwak EL, Schrag D, et al: **Phase 1/2 study of everolimus in advanced hepatocellular carcinoma.** *Cancer* 2011, **117:**5094-5102.
12. Rizell M, Andersson M, Cahlin C, Hafstrom L, Olausson M, Lindner P: **Effects of the mTOR inhibitor sirolimus in patients with hepatocellular and cholangiocellular cancer.** *Int J Clin Oncol* 2008, **13:**66-70.
13. O'Reilly KE, Rojo F, She QB, Solit D, Mills GB, Smith D, Lane H, Hofmann F, Hicklin DJ, Ludwig DL, et al: **mTOR inhibition induces upstream receptor tyrosine kinase signaling and activates Akt.** *Cancer Res* 2006, **66:**1500-1508.
14. Tabernero J, Rojo F, Calvo E, Burris H, Judson I, Hazell K, Martinelli E, Ramon y Cajal S, Jones S, Vidal L, et al: **Dose- and schedule-dependent inhibition of the mammalian target of rapamycin pathway with everolimus: a phase I tumor pharmacodynamic study in patients with advanced solid tumors.** *J Clin Oncol* 2008, **26:**1603-1610.
15. Shi Y, Yan H, Frost P, Gera J, Lichtenstein A: **Mammalian target of rapamycin inhibitors activate the AKT kinase in multiple myeloma cells by up-regulating the insulin-like growth factor receptor/insulin receptor substrate-1/phosphatidylinositol 3-kinase cascade.** *Mol Cancer Ther* 2005, **4:**1533-1540.
16. Wan X, Harkavy B, Shen N, Grohar P, Helman LJ: **Rapamycin induces feedback activation of Akt signaling through an IGF-1R-dependent mechanism.** *Oncogene* 2007, **26:**1932-1940.
17. Chandarlapaty S, Sawai A, Scaltriti M, Rodrik-Outmezguine V, Grbovic-Huezo O, Serra V, Majumder PK, Baselga J, Rosen N: **AKT inhibition relieves feedback suppression of receptor tyrosine kinase expression and activity.** *Cancer Cell* 2011, **19:**58-71.

18. Toker A, Yoeli-Lerner M: **Akt signaling and cancer: surviving but not moving on.** *Cancer Res* 2006, **66:**3963-3966.

19. Fresno Vara JA, Casado E, de Castro J, Cejas P, Belda-Iniesta C, Gonzalez-Baron M: **PI3K/Akt signalling pathway and cancer.** *Cancer Treat Rev* 2004, **30:**193-204.

20. Brodbeck D, Hill MM, Hemmings BA: **Two splice variants of protein kinase B gamma have different regulatory capacity depending on the presence or absence of the regulatory phosphorylation site serine 472 in the carboxyl-terminal hydrophobic domain.** *J Biol Chem* 2001, **276:**29550-29558.

21. Brodbeck D, Cron P, Hemmings BA: **A human protein kinase Bgamma with regulatory phosphorylation sites in the activation loop and in the C-terminal hydrophobic domain.** *J Biol Chem* 1999, **274:**9133-9136.

22. Chen WS, Xu PZ, Gottlob K, Chen ML, Sokol K, Shiyanova T, Roninson I, Weng W, Suzuki R, Tobe K, et al: **Growth retardation and increased apoptosis in mice with homozygous disruption of the Akt1 gene.** *Genes Dev* 2001, **15:**2203-2208.

23. Cho H, Mu J, Kim JK, Thorvaldsen JL, Chu Q, Crenshaw EB, 3rd, Kaestner KH, Bartolomei MS, Shulman GI, Birnbaum MJ: **Insulin resistance and a diabetes mellitus-like syndrome in mice lacking the protein kinase Akt2 (PKB beta).** *Science* 2001, **292:**1728-1731.

24. Grabinski N, Bartkowiak K, Grupp K, Brandt B, Pantel K, Jucker M: **Distinct functional roles of Akt isoforms for proliferation, survival, migration and EGF-mediated signalling in lung cancer derived disseminated tumor cells.** *Cell Signal*, **23:**1952-1960.

25. Santi SA, Lee H: **Ablation of Akt2 induces autophagy through cell cycle arrest, the downregulation of p70S6K, and the deregulation of mitochondria in MDA-MB231 cells.** *PLoS One*, **6:**e14614.

26. Endersby R, Zhu X, Hay N, Ellison DW, Baker SJ: **Nonredundant functions for Akt isoforms in astrocyte growth and gliomagenesis in an orthotopic transplantation model.** *Cancer Res* 2011, **71:**4106-4116.

27. Hirai H, Sootome H, Nakatsuru Y, Miyama K, Taguchi S, Tsujioka K, Ueno Y, Hatch H, Majumder PK, Pan BS, Kotani H: **MK-2206, an allosteric Akt**

inhibitor, enhances antitumor efficacy by standard chemotherapeutic agents or molecular targeted drugs in vitro and in vivo. *Mol Cancer Ther*, **9:**1956-1967.

28. Rosner M, Siegel N, Valli A, Fuchs C, Hengstschlager M: **mTOR phosphorylated at S2448 binds to raptor and rictor.** *Amino Acids*, **38:**223-228.
29. Copp J, Manning G, Hunter T: **TORC-specific phosphorylation of mammalian target of rapamycin (mTOR): phospho-Ser2481 is a marker for intact mTOR signaling complex 2.** *Cancer Res* 2009, **69:**1821-1827.
30. Sarbassov DD, Ali SM, Sengupta S, Sheen JH, Hsu PP, Bagley AF, Markhard AL, Sabatini DM: **Prolonged rapamycin treatment inhibits mTORC2 assembly and Akt/PKB.** *Mol Cell* 2006, **22:**159-168.
31. Wang X, Yue P, Kim YA, Fu H, Khuri FR, Sun SY: **Enhancing mammalian target of rapamycin (mTOR)-targeted cancer therapy by preventing mTOR/raptor inhibition-initiated, mTOR/rictor-independent Akt activation.** *Cancer Res* 2008, **68:**7409-7418.
32. Liao Y, Hung MC: **Physiological regulation of Akt activity and stability.** *Am J Transl Res*, **2:**19-42.
33. Scheid MP, Woodgett JR: **Unravelling the activation mechanisms of protein kinase B/Akt.** *FEBS Lett* 2003, **546:**108-112.
34. Awada A, Cardoso F, Fontaine C, Dirix L, De Greve J, Sotiriou C, Steinseifer J, Wouters C, Tanaka C, Zoellner U, et al: **The oral mTOR inhibitor RAD001 (everolimus) in combination with letrozole in patients with advanced breast cancer: results of a phase I study with pharmacokinetics.** *Eur J Cancer* 2008, **44:**84-91.
35. Chou TC, Talalay P: **Quantitative analysis of dose-effect relationships: the combined effects of multiple drugs or enzyme inhibitors.** *Adv Enzyme Regul* 1984, **22:**27-55.
36. Di Nicolantonio F, Arena S, Tabernero J, Grosso S, Molinari F, Macarulla T, Russo M, Cancelliere C, Zecchin D, Mazzucchelli L, et al: **Deregulation of the PI3K and KRAS signaling pathways in human cancer cells determines their response to everolimus.** *J Clin Invest*, **120:**2858-2866.

37. Reinke A, Chen JC, Aronova S, Powers T: **Caffeine targets TOR complex I and provides evidence for a regulatory link between the FRB and kinase domains of Tor1p.** *The Journal of biological chemistry* 2006, **281:**31616-31626.

38. Ohne Y, Takahara T, Hatakeyama R, Matsuzaki T, Noda M, Mizushima N, Maeda T: **Isolation of hyperactive mutants of mammalian target of rapamycin.** *The Journal of biological chemistry* 2008, **283:**31861-31870.

39. Hardt M, Chantaravisoot N, Tamanoi F: **Activating mutations of TOR (target of rapamycin).** *Genes to cells : devoted to molecular & cellular mechanisms* 2011, **16:**141-151.

40. Sato T, Nakashima A, Guo L, Coffman K, Tamanoi F: **Single amino-acid changes that confer constitutive activation of mTOR are discovered in human cancer.** *Oncogene* 2010, **29:**2746-2752.

41. Lee JW, Soung YH, Kim SY, Lee HW, Park WS, Nam SW, Kim SH, Lee JY, Yoo NJ, Lee SH: **PIK3CA gene is frequently mutated in breast carcinomas and hepatocellular carcinomas.** *Oncogene* 2005, **24:**1477-1480.

42. Tanaka Y, Kanai F, Tada M, Asaoka Y, Guleng B, Jazag A, Ohta M, Ikenoue T, Tateishi K, Obi S, et al: **Absence of PIK3CA hotspot mutations in hepatocellular carcinoma in Japanese patients.** *Oncogene* 2006, **25:**2950-2952.

43. Boyault S, Rickman DS, de Reynies A, Balabaud C, Rebouissou S, Jeannot E, Herault A, Saric J, Belghiti J, Franco D, et al: **Transcriptome classification of HCC is related to gene alterations and to new therapeutic targets.** *Hepatology* 2007, **45:**42-52.

44. Kang S, Bader AG, Vogt PK: **Phosphatidylinositol 3-kinase mutations identified in human cancer are oncogenic.** *Proc Natl Acad Sci U S A* 2005, **102:**802-807.

45. Meric-Bernstam F, Akcakanat A, Chen H, Do KA, Sangai T, Adkins F, Gonzalez-Angulo AM, Rashid A, Crosby K, Dong M, et al: **PIK3CA/PTEN mutations and Akt activation as markers of sensitivity to allosteric mTOR inhibitors.** *Clin Cancer Res*, **18:**1777-1789.

46. Gonzalez E, McGraw TE: **Insulin-modulated Akt subcellular localization determines Akt isoform-specific signaling.** *Proc Natl Acad Sci U S A* 2009, **106:**7004-7009.
47. Gonzalez E, McGraw TE: **The Akt kinases: isoform specificity in metabolism and cancer.** *Cell Cycle* 2009, **8:**2502-2508.
48. Ursini-Siegel J, Schade B, Cardiff RD, Muller WJ: **Insights from transgenic mouse models of ERBB2-induced breast cancer.** *Nat Rev Cancer* 2007, **7:**389-397.
49. Pal SK, Reckamp K, Yu H, Figlin RA: **Akt inhibitors in clinical development for the treatment of cancer.** *Expert Opin Investig Drugs*, **19:**1355-1366.
50. Yap TA, Yan L, Patnaik A, Fearen I, Olmos D, Papadopoulos K, Baird RD, Delgado L, Taylor A, Lupinacci L, et al: **First-in-man clinical trial of the oral pan-AKT inhibitor MK-2206 in patients with advanced solid tumors.** *J Clin Oncol*, **29:**4688-4695.

14 Tables

Table1: Mutation analysis of genes encoding PI3K, mTOR and AKT isoforms in primary HCC samples

Patient ID	PI3KR1	PI3KCA	mTOR	AKT1	AKT2	AKT3
H282			6909 g>ga			
H358	978 g>ga					
H43			6909 g>ga			
H146						
H219	978 g>ga					
H279	978 g>ga		6909 g>ga			
H292	1176 c>ct	3140 a>g	6909 g>ga			
H361			6909 g>ga			
H59			6909 g>ga			
H326						

Table S1: Sequencing primers used for mutation analysis

Gene	**Sequence Primer Forward**	**Sequence Primer Reverse**
PIK3R1Ex9	CCATATTGCATGGAATTGTGAAC	AATGGAACTTAGCAAGCTGGTG
PIK3R1Ex10	TTAAATCTATGTGGGCAGGAGG	TTTCACATCCAATTTGGGATTA
PIK3R1Ex11	GGTAAGCCAGGGAATATAGCTG	TGCAATTATGTAATTACGAGTGTCAAG
PIK3R1Ex12	TTAAAGATGTTTCCATGTCAGCTATT	TTGAAACTCAGTGACTGCTTCAG
PIK3R1Ex13	GCAGTAAGAGATTGTTCTATGAAAGG	TCCACGTGATCATTCAAAGC
PIK3R1Ex14	ATGTTGAGCCACTCCAAAAA	CCCAACCACTCGTTCAACTT
PIK3R1Ex15	TCCAGCTGAGAAAGACGAGAG	TTCAGGGACATCATTATGGACAC
PIK3R1Ex16	GGTATGCCTAGGGAAGACAGC	GGAATCCAAACCTAGTCTTCCAAC
PIK3R1Ex17	CCCAAGTTGAGACTGCACAA	GCCTTAGGCTGCATGTCTTC
PIK3CAEx2a	GCCTAATCAAGTCAAACTATGGAAA	GAAAAAGCCGAAGGTCACAA
PIK3CAEx2b	CACGACCATCATCAGGTGAA	ACGAAGGTATTGGTTTAGACAGA
PIK3CAEx10	CTGTGAATCCAGAGGGGAAA	GCATTTAATGTGCCAACTACCA
PIK3CAEx11	AAAGCTAGTAATGTAAGAAGTTTGGGA	GGGAAAGATAGTTGTGAATGAGC
PIK3CAEx12	GGCAGTGTTTTAGATGGCTCA	CAAATCAGGGTCAGTTTCTGC
PIK3CAEx13	GGTTCGAGGTTTTGCTGTTC	GGAAAACTCTTCCAGCCAAA
PIK3CAEx14	CAGGAACTACCTGAAACTCATGG	CACAATGGCCTTATGAAGCA
PIK3CAEx15	TCTGAGTGTTGCTGCTCTGTG	TTTGAGGGTAGGAGAATGAGAGA
PIK3CAEx16	GGATTCCTAAATAAAAATTGAGGTGA	TGCATATTTCAAAGGTCAAGACA
PIK3CAEx17	CATGTGATGGCGTGATCC	GGTGACACTCCAGAGGCAGTAG
PIK3CAEx18	GGGAAAGGCAGTAAAGGTC	TCAAATATTTCAAAGGTTGAGCA
PIK3CAEx19	TAAATGGAAACTTGCACCCTG	AAACAAATGGCACACGTTCTC
PIK3CAEx20	TGGTGAAAGACGATGGACAAG	TGAGCTCAAGTGATCCTCCA
PIK3CAEx21	GACATTTGAGCAAAGACCTGAAG	TGGATTGTGCAATTCCTATGC
FRAP1Ex44	TGCTGTGCACTTCCTCTGAC	TGCTCTGTGACCTCCATCAG
FRAP1Ex45	CGGGCTCCTGAGGAATATCT	TGCCTCCAGGGAAGAATTTA
FRAP1Ex46	TCCTGGCAGGGTTAACTGTC	GGGAGAAGTGGGTGACAGAA
FRAP1Ex47	TTGAATGCAGTGGTGCTCTC	TGCCCAGCCTTTTTCTTCTA
FRAP1Ex48	TCTGCCTGTGTTCTGAGCTG	TCCCTAGGATGGTGAAAACAA
FRAP1Ex49	CGTTTCTCCTTTTGCCATGT	TGTCTTGCTCACCCATTTCA
FRAP1Ex50	AGCCAAGATAGCACCACTGC	TGGCATCACAATCAATAGGG
FRAP1Ex51	CTCTGCTGTCGTAGCATGGA	AGGTGGTATGGAGGGTAGGG
FRAP1Ex52	AATCAGTGCAGGTGATGCAG	AGAAGGAATCAGGGCAGGAC
FRAP1Ex53	GTGAGTGGCTCTGTCCCATT	CAGCCAAGCAGAACTGTGAG
FRAP1Ex54	CCCACCCACTTATTCCTGAG	TAACAAAGCCCATCCCATTC
FRAP1Ex55	TAGGTAGGGCAGGCGTTAAA	GGTGCCCTGTTTTTCTCAAA
FRAP1Ex56	CCTGAGAGGGGTCAACAAGA	GTGCCAAAGCTCGTCACTAA
FRAP1Ex57	GGCCAAACTTTTCAAATCCA	ACAATGGGCACATGCAGTAA
AKT3Ex1	TTGCTCTGTGAGTTGCAAGAA	CACGCTACACACAACATACCAG
AKT3Ex2	ATTTTTGGAGGCCAGTGTTG	CGATAACCTCTATGCTAAGGGACT
AKT3Ex3	GTTCGCACTGGGTTTTGTTT	TTCTAGCATGCCCAGAGGTT

AKT2Ex2	GCCTTACCCTTTGCTGAGTG	GTCAGATCCCTGCTCTCCTG
AKT2Ex3	TTGTGAGTCACCGTCACACTG	GCTCAATGACCAAGTCCCAC
AKT2Ex4	GGCTTCTCTCCTTCCACACAC	CCAGAAGCGCAGATAGGAAAC
AKT2Ex5	CCCTTCAGCTCTCTCTGGTTC	AGGGCAGCCTTGTCTCTCAG
AKT1Ex3	GAGAGCTTAGAGGGATGGCAG	AGGCACTCACAGACCCTGG
AKT1Ex4	CCTAAGAAACAGCTCCCGTACC	AGCCAGTGCTTGTTGCTTG
AKT1Ex5	TTGGAGAGAGGAAGAGATGGG	AGTGAGGATGGCTACAGGCAG
AKT1Ex6	GTGGAACCACGCTTGTGAG	GTGGAGTGCTGAGTGTCTCCT

15 Letter of Acceptance

Von: BioMed Central Customer Services [mailto:info@biomedcentral.com]
Gesendet: Dienstag, 13. November 2012 18:00
An: Manfred Jücker
Betreff: Please pay the article-processing charge for your article in Molecular Cancer

MS: 3170526247488924

Combined targeting of AKT and mTOR synergistically inhibits proliferation of hepatocellular carcinoma cells

by Nicole Grabinski, Florian Ewald, BiancaT Hofmann, Katharina Staufer, Björn Nashan, Manfred Jücker and Udo Schumacher.

Accepted to Molecular Cancer on 13 November 2012.

Dear Dr Jücker,

We are delighted to confirm that your manuscript has been received by the Production team for publication in Molecular Cancer and we will be in touch with you shortly.

Please remember that the article-processing charge (APC) must be paid prior to publication. Details of the APC for this manuscript, as well as both credit card and invoice payment methods, are available at:
http://www.molecular-cancer.com/author/manuscript/payment/3170526247488924

Please do not hesitate to contact us if you have any questions.

Best wishes,
BioMed Central Customer Services

email: info@biomedcentral.com

16 Zusammenfassende Darstellung der Publikation

16.1 Einleitung

Hepatozelluläre Karzinome (HCC, Leberzellkarzinome) gehören zu den primären Lebertumoren, und gehen von den Hepatozyten als den primären Funktionszellen der Leber aus. Die Inzidenz des HCC zeigt starke Unterschiede in der lokoregionalen Verteilung. Die höchste Inzidenz wird in asiatischen Ländern beobachtet, wobei in der westlichen Welt ein leichter Anstieg der Inzidenz über die letzen Jahrzehnte beobachtet wurde. Regionale Unterschiede in der Inzidenz sind vor allem bedingt durch Unterschiede in der Exposition der Einwohner gegenüber viralen und chemischen Noxen, sowie alimentäre Faktoren. Weltweit ist das HCC momentan die dritthäufigste Todesursache, in vielen Fällen bedingt durch eine späte Diagnosestellung und damit einhergehend eingeschränkter Therapierbarkeit. Die komplette chirurgische Entfernung des Tumors stellt bislang die einzige Möglichkeit dar, eine Heilung zu erzielen. Bei lokal inoperablen Befunden, beispielsweise auf Grund der Ausdehnung oder einer ungünstigen strategischen Lage des Tumors, ist bisher nur eine palliative systemische oder lokale Therapie möglich. Die erste Substanz, für die dabei eine lebensverlängernde Wirkung in klinischen Studien belegt werden konnte, ist der Multityrosinkinaseinhibitor Sorafenib (Llovet et al, 2008). Die Tumorerkrankung schreitet in der Regel jedoch auch unter dieser Therapie weiter fort, sodaß dringender Bedarf an neuen, effektiveren Therapiemöglichkeiten besteht.

In zahlreichen Studien konnte gezeigt werden, daß der PI3K/AKT/mTOR-Signalweg in vielen HCC überaktiviert ist (Chen et al, 2009). Weiterhin konnte gezeigt werden, daß eine Überaktivierung von AKT und mTOR mit einem schlechteren Überleben der Patienten korreliert (Villanueva et al, 2008). Der PI3K/AKT/mTOR Signalweg ist in Tumorzellen unter anderem an der Regulation von Proliferation, Apoptose, Migration und Neoangiogenese beteiligt, sodaß hier ein potentieller Ansatzpunkt für neue Therapiemöglichkeiten gegeben ist (Bhaskar & Hay, 2007). Im Bereich der Immunsuppression werden seit langem Inhibitoren gegen mTOR erfolgreich zur Proliferationshemmung eingesetzt. Diese Substanzen, beispielsweise Rapamycin oder RAD001, sind allosterische Inhibitoren von mTOR, und zeichnen sich durch eine gute orale Bioverfügbarkeit und eine gute Verträglichkeit aus.

In zahlreichen Studien wurde beschrieben, daß mTOR in einen selbstregulierenden Signalweg eingebunden ist. Hiernach kommt es durch Hemmung von mTOR zum Wegfall einer inhibitorischen Feedback-Schleife, und damit u.a. zur Aktivierung der in der PI3K/AKT/mTOR-Signalkaskade weiter oberhalb gelegenen Kinase AKT. AKT selbst nimmt eine zentrale Position in der Regulation von Zellteilung und –Motilität ein, sodaß die Aktivierung von AKT potentiell ein unerwünschtes Ereignis beim onkologischen Einsatz von mTOR-Inhibitoren darstellt. Ziel dieses Projektes war es, diese Feedback Aktivierung von AKT an Hand von drei etablierten HCC-Zellinien auf der Ebene der einzelnen AKT-Isoformen (AKT1, AKT2, AKT3, synonym PKBα, PKBβ und PKBγ) zu charakterisieren, sowie die funktionelle Relevanz einzelner AKT-Isoformen für die Proliferation von HCC-Zellen zu untersuchen. Die Effektivität einer kombinierten mTOR und AKT Inhibition unter Verwendung von RAD001 und MK-2206, einem neuen, allosterischen und oral bioverfügbaren AKT-Inhibitor, wurde dabei als translationaler Ansatz zur Etablierung neuer Tumortherapien sowohl *in vitro* als auch in einem Xenotransplantations-Mausmodell *in vivo* evaluiert.

16.2 Material und Methoden

Drei etablierte HCC-Zellinien (Hep3B, HepG2, Huh7) wurden benutzt, um die *Feedback*-Aktivierung von AKT nach Inhibition von mTOR mittels steigender Konzentrationen von RAD001 zu untersuchen. Dies erfolgte indirekt mittels Detektion von phosphorlyliertem AKT im Western Blot, wobei zwei bekannte Phosphorylierungsstellen, Serin 473 (im weiteren pAKT S473) und Threonin 308 (pAKT T308), als Maß für die Aktivierung von AKT herangezogen wurden, als auch mittels direkter Messung der enzymatischen Aktivität einzelner AKT-Isoformen in einem *in vitro* Kinase Assay. Um Aufschluß über den zeitlichen Verlauf zu erhalten, wurden zusätzlich detaillierte Kinetiken der Feedback Aktivierung von AKT erstellt.

Der dosisabhängige Effekt von RAD001, MK-2206 sowie der Kombination aus beiden Hemmstoffen auf die Proliferation von HCC-Zellinien wurde mittels eines BrdU-ELISA, und der Effekt auf die Zellzyklusverteilung mittels Detektion des zellulären DNA-Gehaltes in der Durchflußzytometrie gemessen.

Zur Untersuchung der funktionellen Relevanz einzelner AKT-Isoformen für die Proliferation der HCC-Zellinien wurden mittels lentiviraler Transduktion und Expression einer entsprechenden shRNA selektiv die Genexpression jeweils einer AKT-Isoform herunter reguliert. Als Kontrolle wurden Zellen mit einem Vektor transduziert, der eine zu keiner kodierenden Sequenz im menschlichen Genom komplementäre shRNA exprimiert. Die Proliferation dieser *knockdown*-Zellen wurde nach Inkubation mit einer Trägersubstanz oder RAD001, sowie für die parentalen Zellen ohne *knockdown* auch nach Inkubation mit MK-2206 oder der Kombination aus RAD001 und MK-2206 bestimmt, in dem der Einbau des Desoxythymidin Analogons BrdU (Bromdesoxyuridin) in der Durchflußzytometrie gemessen wurde.

Zur Etablierung eines HCC Xenotransplantations-Modells wurden 1x10^6 Huh7 Zellen subkutan in die Flankenregion von 8 Wochen alten SCID-Mäusen injiziert. Nach Anwachsen der Tumorzellen wurden die Mäuse oral über eine Schlundsonde mit einer Trägerlösung, RAD001, MK-2206 oder der Kombination aus beiden Substanzen behandelt. Die Applikation von RAD001 in einer Dosierung von 1mg/kg Körpergewicht (KG) erfolgte dabei täglich, die Applikation von MK-2206 mit einer Dosierung von 100mg/kg KG alle zwei Tage montags bis freitags. Alle Mäuse wurden bis zum Erreichen eines Abbruchkriteriums, oder für maximal 22 Tage behandelt, bis alle Mäuse in der Kontrollgruppe aus dem Versuch genommen werden mußten.

16.3 Ergebnisse

Nach Inkubation der HCC-Zellinien mit RAD001 für 24h wurde ein zellinien- und konzentrationsabhängiger Anstieg der Phosphorylierung von AKT beobachtet. Einen Anstieg von pAKT T308 war dabei in allen Zellinien zu beobachten, während ein Anstieg von pAKT S473 nur in zwei Zellinien, Hep3B und Huh7, bei niedrigen Konzentrationen von RAD001 zu beobachten war. Höhere Konzentrationen von RAD001 bewirkten keine Änderung, oder sogar eine Reduktion von pAKT S473. Bei der Analyse des zeitlichen Verlaufes zeigte sich, daß es einige Stunden nach Exposition mit RAD001 auch in HepG2-Zellen zu einem transienten Anstieg von pAKT S473 kommt, während bei einer Inkubation mit RAD001 für mehr als 24h eine Reduktion der Phosphorylierung nachweisbar ist.

Die Analyse der Expression und Kinaseaktivität einzelner AKT-Isoformen im *in vitro* Kinase-Assay ergab zusätzlich eine isoformspezifische Regulation von AKT. Die Expression von AKT3 war dabei nur in Hep3B-Zellen nachweisbar, während die Expression von AKT1 und AKT2 in allen Zellinien nachweisbar war. Während in HepG2-Zellen ein konzentrationsabhängiger Anstieg der Enzymaktivität von AKT1 nach Inkubation mit RAD001 nachweisbar war, wurde eine signifikante Reduktion der Aktivität von AKT2 beobachtet. In Huh7 Zellen hingegen führte die Hemmung von mTOR sowohl zu einem Anstieg der Aktivität von AKT1 als auch der von AKT2. In Hep3B war ein Anstieg der Enzymaktivität von AKT2 nur bei der niedrigsten von Konzentration RAD001 nachweisbar, während höhere Konzentrationen von RAD001 eher eine Reduktion der Kinaseaktivität von AKT1 und AKT3 bewirkten, die jedoch statistisch nicht signifikant war.

In der Untersuchung des Effektes von RAD001 auf die Proliferation von HCC-Zellen zeigte sich interessanterweise in den hier verwendeten Verdünnungen von 1-1000nM keine konzentrationsabhängige Reduktion der Proliferation. Hep3B und Huh7 waren mäßig sensibel gegenüber der Hemmung von mTOR, während HepG2 Zellen eher resistent sind. In keiner Zellinie konnte RAD001 alleine eine Hemmung der Proliferation von mehr als 50% bewirken. Durch pharmakologische Inhibition von AKT mittels MK-2206 konnten wir für alle Zellen eine signifikante Reduktion der Proliferation im BrdU ELISA nachweisen, mit IC_{50} Werten von 3,7, 7,4 und 3,1 µM für Hep3B, HepG2 und Huh7. Durch Kombination von RAD001 und MK-2206 konnten starke synergistische Effekte in den drei Zellinien hervorgerufen werden, was mittels des von Chou und Talalay beschriebenen Verfahrens quantitativ bestätigt wurde.

Die lentivirale Ausschaltung der Genexpression einer AKT-Isoform konnte in allen Zellinien mit hoher Effizienz durchgeführt werden, wobei nur für Hep3B-Zellen ein *Knockdown* von AKT3 durchgeführt wurde. Die Hemmung von AKT1 führte in allen Zellinien zu einer signifikanten Reduktion der Proliferation, am ausgeprägtesten in Hep3B-Zellen. Die Hemmung von AKT2 führte nur in Hep3B- und HepG2-Zellen zu einer signifikanten Reduktion der Proliferation, während die Hemmung von AKT3 in Hep3B-Zellen keinen signifikanten Einfluß auf die Proliferation hatte. Durch die selektive Hemmung von AKT1 konnte in allen drei HCC-Zellinien eine synergistische Reduktion der Proliferation bei gleichzeitiger Behandlung mit RAD001 erzielt werden, während die Hemmung von AKT2 oder AKT3 keinen synergistischen Effekt hervorrief.

Um den Effekt einer gleichzeitigen, pharmakologischen Hemmung von AKT und mTOR *in vivo* zu untersuchen, wurden Huh7-Zellen subkutan in SCID-Mäuse injiziert. Drei Wochen nach Injektion der Tumorzellen waren in allen Mäusen subkutane Tumoren nachweisbar, und die Mäuse wurden nach dem Anwachsen des Tumors bis zu 22 Tagen oral mit einer Placebolösung (Trägerlösung), RAD001, MK-2206 oder der Kombination aus RAD001 und MK-2206 behandelt. Dabei zeigte sich, daß nur die Kombination beider Hemmstoffe in der Lage war, das Überleben der Versuchstiere signifikant zu verlängern, und das Tumorvolumen signifikant zu reduzieren. Unter keiner Behandlung wurden Hinweise für unerwünschte Nebenwirkungen beobachtet.

16.4 Diskussion

Wir konnten in unserer Studie zeigen, daß Veränderungen in der Aktivierung von AKT nach mTOR-Inhibition zellinien- und zeitabhängig sind. Eine Zunahme der Phosphorlyierung von AKT an S473, die für die volle enzymatische Aktivität von AKT erforderlich ist, war dabei nur in zwei von drei Zellinien, und nur innerhalb der ersten 12 bis 24h nachweisbar. Für die Phosphorylierung von AKT an S473 ist hauptsächlich mTORC2 verantwortlich, und unsere Ergebnisse sind gut mit den Daten von Sarbassov et al. vereinbar, die zeigen konnten, daß eine längerfristige (>24h) Inkubation von Zellen mit einem allosterischen mTOR-Inhibitor nicht nur mTORC1, sondern auch indirekt mTORC2 hemmt. Dies geschieht über die Bindung von freiem mTOR an FK506 binding protein 12 (FKBP12), sodaß kein mTOR für die Bildung von mTORC2 zur Verfügung steht.

Ein Anstieg der Phosphorylierung von AKT an T308 war hingegen in allen Zellinien nachweisbar. Dies paßt zu dem von Shi et al. beschriebenen Modell, wonach durch Hemmung von mTOR eine inhibitorische Rückkopplung auf IRS-1 wegfällt, wodurch es zu einer vermehrten Aktivierung der PI3K, und damit von PDK-1 kommt. Für letzteres Enzym wurde gezeigt, daß es hauptverantwortlich für die Phosphorylierung von AKT an T308 ist. In neueren Studien von Chandarlapaty et al. konnte mittlerweile gezeigt werden, daß die Inhibition von mTOR nicht nur die Expression von IRS-1, sondern auch einer Reihe anderer Rezeptortyrosinkinasen induziert. Dies paßt zu den von uns erhobenen Daten, daß ein Anstieg der Proteinmenge von IRS-1 nur in Huh7 Zellen nachweisbar war, während alle Zellinien einen deutlichen Anstieg von pAKT T308 zeigten. Weiterhin wurde kürzlich von Rodrik-Outmezguine et al. gezeigt, daß die Inkubation von Tumorzellen mit mTOR-Inhibitoren neuerer Generation (AZD8055), die über eine direkte, kompetitive Inhibition von mTORC1 und mTORC2 wirken, die Phosphorylierung von AKT an S473 komplett unterbunden werden kann. Jedoch wurde auch in Tumorzellen, die mit diesen Inhibitoren für 24h behandelt wurden, eine AKT Kinaseaktivität von etwa 60% des Ausgangswertes gemessen, sodaß, im Gegensatz zu früheren Untersuchungen zur Rolle der

Phosphorylierungsstellen an AKT, davon ausgegangen werden kann, daß die Phosphorylierung von AKT an T308, ohne Phosphorylierung an S473, für eine enzymatische Aktivität ausreichend ist. Dies unterstütz unsere Beobachtung, daß in der HCC-Zellinie Huh7, die 24h nach Inkubation mit RAD001 keine Steigerung der Phosphorylierung von AKT an S473 zeigt, dennoch eine Steigerung in der Enzymaktivität sowohl von AKT1, als auch von AKT2 nachweisbar ist. Weiterhin konnten wir erstmalig zeigen, daß die enzymatische Aktivität von AKT-Isoformen differentiell reguliert werden kann, wie für die HCC-Zellinie HepG2 gezeigt, die nach Behandlung mit RAD001 einen Anstieg der Aktivität von AKT1, nicht aber von AKT2 zeigt. Vor dem Hintergrund, daß AKT-Isoformen auch exklusive, und teilweise gegenläufige Funktionen haben können, ergeben sich hieraus hochkomplexe Regulationsmöglichkeiten. Zu einem genaueren Verständnis sind jedoch weitere Untersuchungen notwendig.

Das zweite zentrale Ergebnis unserer Studie ist der Nachweis eines ausgeprägten synergistischen Effektes einer gleichzeitigen Inhibition von mTOR und AKT durch die Kombination von RAD001 und MK-2206 sowohl *in vitro* als auch *in vivo*. Da zu RAD001 (Everolimus, Afinitor) und anderen mTOR-Inhibitoren wie Rapamycin (Sirolimus) und MK-8669 (Ridaforolimus) bereits umfangreiche klinische Erfahrungen vorliegen, und MK-2206 aktuell in Phase II Studien erprobt wird, erscheint ein zukünftiger klinischer Einsatz dieser Kombinationsbehandlung zur Therapie von fortgeschrittenen hepatozellulären Karzinomen möglich. Die Kombination aus Ridaforolimus (MK-8669) als allosterischer mTOR-Inhibitor und MK-2206 wird bereits für die Behandlung von fortgeschrittenen, soliden Tumorerkrankungen im Rahmen zweier Phase I Studien erprobt (Clinical Trials Identifier NCT01295632 und NCT01243762). Die Ergebnisse unserer Studie deuten dabei auf eine dominante Rolle von AKT1 und AKT2, und weniger AKT3 für die Proliferation von HCC-Zellen hin. Dies ist interessant vor dem Hintergrund der Entwicklung AKT-Isoform spezifischer Inhibitoren, durch deren Einsatz sich das Nebenwirkungsspektrum einer Inhibition aller AKT-Isoformen möglicherweise verbessern ließe. Zu beachten ist dabei, daß die Expression und funktionelle Relevanz einzelner AKT-Isoformen nach dem heutigen Verständnis gewebeabhängig ist, und AKT3 beispielsweise in Melanomen und Mammakarzinomen eine prädominante Rolle spielt. Zur Bestätigung dieser Hypothese sind jedoch weitere Untersuchungen nötig.

16.5 Erklärung des Eigenanteils an der Publikation

Die hier beschriebenen AKT-Isoform spezifischen *in vitro* Kinase Assays wurden von Frau Dr. Nicole Grabinski durchgeführt. Alle weiteren, in der Kurzzusammenfassung beschriebenen Experimente wurden von mir eigenständig durchgeführt.

17 Danksagung

Ich danke Herrn Prof. Nashan und Herrn PD. Dr. Jücker für die Bereitstellung des interessanten Themas, und die Unterstützung bei der Durchführung des Projektes.

Ich danke Frau Dr. Grabinski für die produktive und inspirierende Zusammenarbeit im Labor.

Für die hilfreichen Tipps und die Unterstützung bei den Mausexperimenten möchte ich mich bei Prof. Schumacher, Frau Feldhaus Herrn Gosau bedanken.

Ich möchte mich bei der Novartis Pharma GmbH für die finanzielle Unterstützung sowie beim UCCH für die Unterstützung im Rahmen des Forschungsstipendiums bedanken.

18 Lebenslauf

Florian Ewald
Geboren am 29.10.1984 in Lemgo, NRW, Deutschland
Nationalität: Deutsch
Familienstand: ledig

Schulbildung

1990 – 2003 Grundschule Bad Meinberg, Hermann-Vöchting-Gymnasium Blomberg; Abschluß mit allgemeiner Hochschulreife (Note: 1,9)

Universitätslaufbahn

- **Studium der Physik an der Universität Paderborn** im Sommersemester 2004

- **Studium der Humanmedizin an der Universität Hamburg** ab Wintersemester 2004/2005

  1. Abschnitt der Ärztlichen Approbation Herbst 2006, Gesamtnote:
  sehr gut (1,5)

  Famulaturen
  Neurologie, Klinik und Poliklinik für Neurologie, UKE, 2007
  General Medicine, Eastbourne District General Hospital, GB, 2008
  Kardiologie, MVZ Prof. Schofer, Prof. Mathey, Universitäres Herzzentrum Hamburg, 2008
  Radiologie, Klinik für diagnostische und interventionelle Radiologie, UKE, 2009

  Praktisches Jahr, 8/2009 bis 7/2010
  Neurologie, Klinik und Poliklinik für Neurologie, UKE
  Onkologie, II. Medizinische Klinik, UKE
  Gastroenterologie, I. Medizinische Klinik, UKE
  Viszeral-, Thorax- und Tumorchirurgie, Albertinen-Krankenhaus Hamburg
  Notfallchirurgie, Notfallzentrum Inselspital, Bern, CH

  2. Abschnitt der Ärztlichen Approbation, Herbst 2010, Gesamtnote:
  sehr gut (1,0)

  Erteilung der ärztlichen Approbation November 2010, Gesamtnote:
  sehr gut (1,16)

- **Wissenschaftlicher Mitarbeiter der Klinik und Poliklinik für Hepatobiliär- und Transplantationschirurgie**, UKE Hamburg, seit Januar 2011

  Aufbaustudium Molekularbiologie am ZMNH seit 10/2011
  Forschungsförderung im Rahmen des UCCH-Forschungsstipendiums 2012

19 Eidesstattliche Versicherung

Ich versichere ausdrücklich, dass ich die Arbeit selbständig und ohne fremde Hilfe verfasst, andere als die von mir angegebenen Quellen und Hilfsmittel nicht benutzt und die aus den benutzten Werken wörtlich oder inhaltlich entnommenen Stellen einzeln nach Ausgabe (Auflage und Jahr des Erscheinens), Band und Seite des benutzten Werkes kenntlich gemacht habe.

Ferner versichere ich, dass ich die Dissertation bisher nicht einem Fachvertreter an einer anderen Hochschule zur Überprüfung vorgelegt oder mich anderweitig um Zulassung zur Promotion beworben habe.

Ich erkläre mich einverstanden, dass meine Dissertation vom Dekanat der Medizinischen Fakultät mit einer gängigen Software zur Erkennung von Plagiaten überprüft werden kann.

Unterschrift: ....