AD_____

Award Number:
W81XWH-09-1-0028

TITLE:
Regulation of Mammary Progenitor Cells by p53 and Parity

PRINCIPAL INVESTIGATOR:
Luwei Tao MD
D. Joseph Jerry, PhD

CONTRACTING ORGANIZATION:
University of Massachusetts
Amherst, Massachusetts, 01003

REPORT DATE:
January 2011

TYPE OF REPORT:
Annual Summary

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT:

√ Approved for public release; distribution unlimited

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE: \	2. REPORT TYPE:	3. DATES COVERED *(From - To)*
31-Jan-2011	AnnualSummary	1 JAN 2010 - 31 DEC 2010

4. TITLE AND SUBTITLE

Regulation of Mammary Progenitor Cells by p53 and Parity

5a. CONTRACT NUMBER

W81XWH-09-1-0028

5b. GRANT NUMBER

W81XWH-09-1-0028

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Luwei Tao, D. Joseph Jerry

luwei@mcb.umass.edu

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of Massachusetts
Amherst, Massachusetts, 01003

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S.Army Medical Research and Material Command
Fort Detrick, Maryland, 21702-5012

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Breast cancer is the most common tumor among women with inherited mutations in the p53 gene (Li-Fraumeni syndrome). The tumors represent the basal-like subtype which has been suggested to originate from mammary stem/progenitor cells. In mouse mammary epithelium, mammosphere-forming potential was increased with decreased dosage of the gene encoding the p53 tumor suppressor protein (*Trp53*). Limiting dilution transplantation also showed a 3.3-fold increase in the frequency of long-term regenerative mammary stem cells in *Trp53-/-* mice. The repression of mammospheres by p53 was apparent despite the absence of apoptotic responses to radiation indicating a dissociation of these two activities of p53. The frequency of long-term label-retaining epithelial cells (LRECs) was decreased in *Trp53-/-* mammary glands indicating that asymmetric segregation of DNA is diminished and contributes to the expansion of the mammary stem cells. Progenitor cell was also labeled with let-7c sensor. The knockdown of p53 also significantly increased the number of DsR+ progenitor cells *in vitro*. Treatment with an inhibitor of gama-secretase (DAPT) reduced the number of *Trp53-/-* mammospheres to the level found in *Trp53+/+* cells. These results demonstrate that basal levels of p53 restrict mammary stem/progenitor cells through Notch and that the Notch pathway is a therapeutic target to prevent expansion of this vulnerable pool of cells.

15. SUBJECT TERMS

p53, parity, stem cells, progenitor cells, ionizing radiation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					USAMRMC
a. REPORT	b. ABSTRACT	c. THIS PAGE	UU	36	19b. TELEPHONE NUMBER *(include area code)*
U	U	U			

Standard Form 298 (Rev. 8-98)

Table of Contents

Page

Introduction

Breast cancer is the most frequent cancer among women in the United States[1]. Understanding the biological behavior of mammary stem cells (MaSCs) and progenitor cells sheds light on the mechanism of mammary gland malignant transformation [2,3]. A full term pregnancy early in reproductive life can reduce breast cancer incidence in women by up to 50% [4]. The research in our lab has shown that the p53 tumor suppressor pathway is a crucial downstream mediator for this protection mechanism [5,6]. Parous mammary epithelium showed significantly higher apoptotic response to ionizing radiation (IR) which was p53-dependent [7,8]. Recent research showed p53 also participated in the regulation of tissue-specific stem cells in both hematopoietic system and neural system. Furthur more, *Arf-Trp53* pathway was shown to restrict the efficiency of reprogramming of induced pluripotent stem cells [9,10].

We propose that p53 negatively regulates the proliferation and self-renewal of mammay stem.progenitor cells. The increased p53 activity in parous gland may reduce the mammary progenitor/stem cell pool resulting in decreased risk of mammary tumors. In the past year of research, we focused on testing the role of p53 in our *in vitro* model of TM40A cell line. We confirmed that p53 negatively regulated mammary stem/progenitor cells proliferation and self-renewal in both primary mammary epithelial cells and TM40A cell line. The loss of p53 led to increased mammary stem/progenitor cells population, which may be a vulnerable population of transformation. We further showed that the γ-secretase inhibitor can effective block the expansion of p53 defective mammary stem/progenitor cells, which can be a potential therapeutic target to prevent the expansion of this vulnerable pool of cells.

Body

Methods

Mammosphere culture

Primary single cells were seeded into ultra-low attachment dishes or plates at a density of 20,000 viable cells/ml. Cells were grown in a serum-free mammary epithelial growth medium (HuMEC, Gibco) supplemented with B27 (Gibco), 20ng/ml EGF (Sigma), 20ng/ml bFGF (Sigma), 4 μg/ml heparin (Sigma), 100u/ml Pen/Strep, 5 μg/ml gentamicin [11]. For the GSI treatment, N-[N-(3,5-Difluorophenacetyl)-L-alanyl]-S-phenylglycine t-butyl ester (DAPT, Sigma) was added into culture medium to the final concentration of 5 μM (final DMSO concentration 0.1%). To passage mammospheres, mammospheres were collected with gentle centrifugation 800rpm for 5m in 7 days after culture and dissociated with 1ml pre-warmed 0.05%Trypsin-EDTA and 60 μl 1mg/ml DNase I for 5-8m in. Cell suspensions obtained from dissociation were sieved through 40 μm cell strainer and seeded at a density of 1,000 viable cells/ml.

TM40A cell culture and retroviral infection

TM40A cells were maintained in regular MECL media: DMEM:F12 supplemented with 2% adult bovine serum (Gibco), 10μg/ml Insulin (Sigma), 20ng/ml mEGF, and 100u/ml Pen/Strep.. let-7c sensor plasmids and the control plasmids are gifts from Dr. Gregory Hannon. pSicoR-PGK-puro vector plasmid was purchased (Addgene, Cambridge, MA). Oligos coding for the p53 knockdown or scramble shRNA were annealed and cloned into pSicoR-PGK-puro vector. The p53 target sequence was 5'-GTACTCTCCTCCCCTCAAT-3' and the scramble sequence was 5'-CGCTACACACTTCTTCTCC-3'. The infection of TM40A cells with let-7c sensor plasmid, pSicoR-PGK-puro-p53KD plasmid or the control plasmids were performed as described previously [12,13].

Western blot

TM40A cell protein lysates were harvested 1 hour after 0-Gy or 10-Gy of γ-irradiation using RIPA buffer (50mM Tris, 150mM NaCl, 1% TritonX-100, 10% glycerol, 0.1% SDS, 0.5% deoxycholate, 1x protease inhibitor (Sigma, p8340) and 1x phosphatase inhibitor (Sigma, P5726)). Protein lysates (80 μg) were separated by 10% SDS-PAGE and transferred to PVDF membrane (Millipore, Billerica, MA). The membrane was incubated with anti-phospho p53 (1:1000, Cell Signaling, 9284), or anti- β-actin (1:4000, Sigma, A1978), followed by incubation with hoseradish peroxidase conjugated secondary antibodies (1:5000, GE Healthcare, Little Chalfont, Buckinghamshire, UK), and developed using enhanced chemiluminescence (ECL) solution (GE Healthcare) in G:Box imaging system (Syngene, Cambridge, UK).

PCR and knock down of Notch1 using siRNA

Notch1 forward primer: 5'-TGGACGACAA TCAGAACGAG-3', Notch1 reverse primer: 5'-GGAGAACTACTGGCTCCTCAAA-3'; Notch4 forward primer: 5'-TCCGTCCTGAGGGCTATTC-3', Notch4 reverse primer: 5'-ACACAGGTACCCCCATTGAG-3';Hes-1 forward primer: 5'-TGCCAGCTGATATAATGGAGAA-3', Hes-1 reverse primer: 5'-CCATGATAGGCTTTGATGACTTT-3'; PGK forward primer: 5'-TACCTGCTGGCTGGATGG-3', PGK reverse primer: 5'- CGCAGCCTCGGCATATTTCT-3'. Mammospheres were cultured as described above. Primary mammospheres were passaged to secondary mammospheres and total RNA were harvested and quantified 3 days after passage. Reverse transcription were done using RT kit(Roche). Quantitative PCR was done using Roche

Universal library and real-time quantitative PCR system (Stratagene). To knockdown Notch1 in TM40A cells, siRNA (s70698 and s70700) were purchased from Ambion. s70698 siRNA sense sequence: 5'- CUAUGGUACUUAUAAGUGU tt-3', antisense sequence: 5'- ACACUUAUAAGUACCAUAGct-3'. S70700 siRNA sense sequence: 5'- GGAUGUCAAUGUUCGAGGAtt-3', antisense sequence: 5'- UCCUCGAACAUUGACAUCCat-3'. siRNA oligos were diluted into 100 μM working stock and 3 different siRNA concentrations (12.5pmol/well, 37.5pmol/well and 75pmol/well) were tried for transfection of TM40A cells using Lipofectamin 2000 (Invitrogen). Total RNA were isolated 48 hours after transfection and real-time quantitative PCR was used to confirm the knockdown efficiency.

Results

Label and chase progenitor cells population *in vitro* using let-7c sensor plasmid

The role of p53 in regulation of mammary stem/progenitor cells was further confirmed *in vitro* using the TM40A cell line, a mammary epithelial cell line derived from BALB/c mice and retains wild type p53 mRNA (unpublished data, DJJ). TM40A cells form hyperplastic outgrowths when transplanted *in vivo* (Fig. 1A) but have undetectable tumorigenicity through 20 weeks. The let-7 microRNA family was shown to be depleted in the mammary progenitor cells and highly expressed in the more differentiated cell types and the let-7c sensor plasmid (let7^{s}) has been used to label mammary progenitor population *in vitro* [12]. After infected with let-7c sensor plasmids, the TM40A-let7^{s} cells contained 0.8% of DsRed positive (DsR^{+}) progenitor cells (Fig. 1B). The mammosphere-forming capacity of DsR^{+} cells is 3.8-fold greater than DsR^{-} cells ($p<0.01$) (Fig. 1C), confirming their progenitor feature. Interestingly, most of the cells in the DsR^{+} mammospheres remained DsR^{+} (Fig. 1D), suggesting the inhibition of differentiation under the mammosphere culture condition.

TM40A cells as *in vitro* model to study the role of p53 in the regulation of stem/progenitor cells

We proceeded to determine whether the knockdown of p53 can change the proportion of DsR^{+} progenitor cells as well. TM40A-let7^{s} cells were infected with a p53 shRNA plasmid (TM40A-let7^{s}-p53KD) or control plasmid (TM40A-let7^{s}-ctrl) as described previously [13]. Infection of TM40A-let7^{s} cells with p53 shRNA plasmid effectively decreased p53 protein to less than 24% of the original level (Fig. 2A). The transactivation activity of p53 also significantly decreased as shown by luciferase assay (Fig. 2B). After the knockdown of p53, the TM40A-let7^{s}-p53KD contained increased numbers of DsR^{+} cells (2.5 %) compared to the TM40A-let7^{s}-ctrl cells (0.8%) (Fig. 3A and B). The number of secondary mammospheres formed by TM40A-let7^{s}-p53KD cells was also 2.2-fold higher than the control cells ($p<0.01$) (Fig. 3E), further proving that the basal level of p53 inhibits the expansion of mammary progenitor cells. TM40A cells can be a usefully *in vitro* model to study the detailed molecular mechanism of how p53 regulates the self-renewal and proliferation of mammary stem/progenitor cells. Furthermore, the TM40A-let7^{s} cells allowed use to track the behavior of mammary progenitor cells in the future and study the transformation process of mammary progenitor cells.

Notch inhibitor reduced the number of mammary stem/progenitor cells

Increased mammary stem/progenitor cells could be vulnerable targets for carcinogenesis, especially in Li-Fraumeni patients in whom p53-mediated genome surveillance is compromised. We proceeded to test the potential of pharmacological methods to inhibit the expansion of

mammary stem/progenitor cells. The Notch pathway has been reported to both promote and limit progenitor cells [14,15], therefore we tested whether γ-secretase inhibitors (GSI), could affect the expansion of p53-deficient mammary stem/progenitor cells [16,17]. The number of TM40A-let7^{s}-p53KD mammospheres decreased to baseline levels after the treatment with DAPT, a GSI (Fig. 3E; $p<0.01$) indicating that Notch pathway could be a potential therapeutic target for downregulation of mammary stem/progenitor cells. The number of mammospheres in control cells with wild type p53 was not changed with DAPT treatment showing that inhibition of Notch was not a general effect, but specifically reversed the effect of p53-deficiency (Fig. 3E). DAPT treatment also restricted the expansion of progenitors measured by DsR^{+} sensor after p53 knockdown. In TM40A-let7^{s}-p53KD cells, DAPT decreased the DsR^{+} cells from 2.5% to 1.4% (compare Fig. 3B and D), whereas the proportion of DsR^{+} cells was not changed by DAPT in the control group (compare Fig.3A and C). *Trp53-/-* and *Trp53+/+* primary mammary epithelial cells were also treated with 5 μM DAPT or DMSO. Similarly, DAPT significantly inhibited the expansion of *Trp53-/-* mammospheres. The number of *Trp53-/-* secondary mammospheres decreased significantly from 250±13.4/10,000 cells to 168.3 ±11.4/10,000 cells after the DAPT treatment ($p<0.01$), but the number of *Trp53+/+* mammospheres were not affected (Fig. 3F).

Test the level of Notch pathway components in mammospheres of different *Trp53* genotype

The inhibition of mammary stem/progenitor cell number by GSI also suggested that the Notch pathway may play role in the regulation of mammary stem/progenitor cells self-renewal. p53 was reported to inhibit the activation of Notch pathway at different levels by either inhibiting the transcription of presenilin-1 or competing with Notch-1 intracellular domain for coactivator p300/CBP [18-20]. We hypothesize that Notch pathway may upregulate the self-renewal and proliferation of mammary stem/progenitor cells. The loss of p53 releases the inhibition effects and leads to the increased mammary stem/progenitor cells number (Fig. 3G). In order to test whether the loss of p53 leads to increased activity of Notch pathway, Notch1, Notch4 and Hes-1 primers were designed and used for PCR. We found no significant difference in the level of Notch1, Notch4 or Hes-1 level between *Trp53+/+* and *Trp53-/-* mammospheres (Fig. 4 A and B). We also tried a couple of commercially available antibodies for mice Notch1 or Notch4. However, none of these antibodies gave us specific band. Our previous experiments showed that mammsphere-initiating cell is a very small population among all the cells in mammosphere. It is possible that the Notch pathway may play different roles in different cell types. The mixed cell population can mask the difference of Notch levels in the small stem/progenitor cell population.

Knock down of Notch1 in TM40A cells using siRNA

In order to confirm the role of Notch pathway in the regulation of mammary stem/progenitor cells, we tried to knockdown Notch pathway in TM40A cells using siRNA. QPCR was carried out to confirm the knockdown efficiency. Preliminary data showed that the siRNA did not effectively knockdown the Notch1 mRNA level in TM40A cells (Fig. 5 A and B). Trouble shooting using FITC-labeled unspecific siRNA showed that the TM40A cells can only be transfected with siRNA at low cell confluency (~30%). For the next step experiments, we will try to knockdown Notch1 at low cell confluency and see if the knockdown of Notch1 can inhibit the expansion of p53-deficient mammary stem/progenitor cells.

Key Research Accomplishments

Jan 2010- Apr 2010 Label mammary progenitor cells *in vitro* using let-7c sensor plasmids and TM40A cells line.

Apr 2010- Jun 2010 Knockdown p53 in TM40A cells using lentiviral shRNA plasmids and confirm the knockdown efficiency.

Jun 2010- Sept 2010 Test different γ-secretase inhibitor and find that DAPT treatment can effectively inhibit the expansion of p53-deficient mammary stem/progenitor cells *in vitro*.

Jul 2010- Oct 2010 Write manuscript: Repression of Mammary Stem/Progenitor Cells by P53 is Mediated by Notch and Separable from Apoptotic Activity. The manuscript summarized the data and progression of this project so far. Submitted the manuscript to Stem Cells, which accepted the manuscript in October, 2010.

Oct 2010- Dec 2010 Test the level of Notch pathway components in mammosphere cells.

Nov 2010- Jan 2011 Knockdown Notch1 in TM40A cells using commercially available siRNA

Reportable outcomes

1. The manuscript: Repression of Mammary Stem/Progenitor Cells by P53 is Mediated by Notch and Separable from Apoptotic Activity, which is funded by this training grant, has been accepted and published in Stem Cells. (See Appendices)
2. Attended the first AACR International Conference on Frontiers in Basic Cancer Research. Presented poster entitled: Regulation of Mammary Stem/Progenitor Cells by p53.
3. Labeled progenitor cells in TM40A cell line using let-7c sensor plasmids. Get TM40A-let7^{s} and control cell lines, which will be useful for tracking progenitor cells *in vitro*.
4. Knockdown p53 in TM40A cells using shRNA. Get TM40A-let7^{s}-p53KD and control cell lines, which were used to confirm the role of p53 in the regulation of mammary stem/progenitor cells in vitro.
5. Prove that γ-secretase inhibitor (DAPT) can be a therapeutic target to inhibit the expansion of p53-deficient mammary stem/progenitor cells.
6. Test the level of Notch pathway components (Notch1, Notch4 and Hes-1) in *Trp53*+/+ and *Trp53*-/- mammospheres using QPCR and Western blot.
7. Applied for a sponsored research opportunity in Brigham and Women's hospital. This position will lead to collaboration between Dr. Jerry's lab and Dr. Li's lab to study the potential role of mammary stem/progenitor cells during malignant transformation.

Conclusions

The importance of p53 in breast cancer is highlighted by the dramatic increase of breast cancer risk among women with Li-Fraumeni syndrome. Although the function of activated p53 in mammary epithelium has been extensively studied, its role at basal level under normal conditions is not fully understood, largely due to the extreme low protein level [21-23]. The comparison of transgenic mice with different *Trp53* genotype allows us to study the function of basal level p53 in mammary epithelium. In last annual report, we showed that the basal level p53 is essential in for the regulation of mammary stem/progenitor cells self-renewal and proliferation and that the regulation of mammary stem/progenitor cells is independent of the apoptosis-mediating function of p53. Insufficient p53 dosage led to increased mammary stem/progenitor cells, which could be a vulnerable target of transformation.

In the past year, we established an *in vitro* system to label and track mammary stem/progenitor cells in our model cell line, TM40A. We showed that the let-7c sensor plasmid can be used to label mammary progenitor cells, which is about 0.8% of total TM40A cell population. The progenitor feature of these cells was further confirmed with mammosphere assay. Similar to the primary mammary epithelial cells, the knockdown of p53 in TM40A cells significantly increased the number of DsR^+ progenitor cells in the total population, suggesting that the TM40A cells could be used as a valuable *in vitro* model to study the role of p53 in the regulation of mammary progenitor cells self-renewal and proliferation.

We further tested whether there is any therapeutic target that we can apply to inhibit the expansion of mammary stem/progenitor cells in the p53-deficient background. We found that γ-secretase inhibitor, DAPT, can effectively inhibit the expansion of progenitor cells. In TM40A-let7^s-p53KD cells, DAPT treatment effectively brought down the DsR^+ cells from 2.5% to 1.4%. By using mammosphere assay, the DAPT treatment also significantly inhibits the mammosphere formation of both *Trp53-/-* primary mammary epithelial cells and the p53 knockdown TM40A cells, without affecting the mammosphere formation of cells with normal functional p53. Women with Li-Fraumeni syndrome, which is commonly associated with germline heterozygous mutations of *TP53*, have significantly increased risk of breast cancer [24,25]. Therefore, the γ-secretase inhibitor can be a good pharmaceutical candidate for Li-Fraumeni syndrome patients, who may benefit from the inhibition of expansion of mammary stem/progenitor cells.

Based on our present data, we hypothesized our working model of disparate functions and roles of p53 in different cell differentiation stages. In differentiated cells, p53 can be activated due to various genotoxic or cellular stresses so that the damaged cells with either be repaired or eliminated through apoptosis, depending on the extent of damage. In contrast, the apoptosis-inducing function of p53 is compromised in the mammary stem/progenitor cells, which may prevent the premature aging process due to DNA damage or other cellular challenges. In these cells, the major tumor suppressor function of p53 is to restrict self-renewal and inhibit inappropriate expansion of mammary stem/progenitor cells, which is independent of the pro-apoptotic role of p53. This function of p53 may either be a direct effect or mediated through the regulation of other pathways, such as Notch, which can be potential therapeutic target for chemoprevention of breast cancer (Fig. 3G).

γ-secretase inhibitor is commonly used to inhibit the cleavage and activation of Notch pathway. The fact that DAPT can effectively inhibit the expansion of mammary stem/progenitor cells

suggested that the Notch pathway may be an important regulator for the mammary stem/progenitor cells self-renewal and proliferation. We tried to look for the levels of Notch pathway components, such as Notch1, Notch4 and Hes-1, in mammospheres and did not find significant difference. It could due to the mixed cell population in the mammosphere. Notch-Numb pathway was shown to play different roles in cells of different differentiation stages. We may want to sort out the DsR^+ progenitor cells and try to look for the Notch pathway components level in those cells. We will also need to optimize the knockdown of Notch1 and Notch4 using siRNA and see if it has similar effects as the γ-secretase inhibitor treatment. This will help us to determine whether the γ-secretase inhibitor actually inhibit the expansion of mammary stem/progenitor cells by inhibiting the activation of Notch pathway.

References

1. Jemal, A. *et al.* Cancer statistics, 2007. *CA Cancer J. Clin.* **57**, 43-66 (2007).

2. Shackleton, M. *et al.* Generation of a functional mammary gland from a single stem cell. *Nature* **439**, 84-88 (2006).

3. Stingl, J. *et al.* Purification and unique properties of mammary epithelial stem cells. *Nature* **439**, 993-997 (2006).

4. Rosner, B., Colditz, G. A. & Willett, W. C. Reproductive risk factors in a prospective study of breast cancer: the Nurses' Health Study. *Am. J. Epidemiol.* **139**, 819-835 (1994).

5. Jerry, D. J. *et al.* A mammary-specific model demonstrates the role of the p53 tumor suppressor gene in tumor development. *Oncogene* **19**, 1052-1058 (2000).

6. Jerry, D. J. Roles for estrogen and progesterone in breast cancer prevention. *Breast Cancer Res.* **9**, 102 (2007).

7. Becker, K. A. *et al.* Estrogen and progesterone regulate radiation-induced p53 activity in mammary epithelium through TGF-beta-dependent pathways. *Oncogene* **24**, 6345-6353 (2005).

8. Dunphy, K. A., Blackburn, A. C., Yan, H., O'Connell, L. R. & Jerry, D. J. Estrogen and progesterone induce persistent increases in p53-dependent apoptosis and suppress mammary tumors in BALB/c-Trp53+/- mice. *Breast Cancer Res.* **10**, R43 (2008).

9. Meletis, K. *et al.* p53 suppresses the self-renewal of adult neural stem cells. *Development* **133**, 363-369 (2006).

10. Dumble, M. *et al.* The impact of altered p53 dosage on hematopoietic stem cell dynamics during aging. *Blood* **109**, 1736-1742 (2007).

11. Dontu, G. *et al.* In vitro propagation and transcriptional profiling of human mammary stem/progenitor cells. *Genes Dev.* **17**, 1253-1270 (2003).

12. Ibarra, I., Erlich, Y., Muthuswamy, S. K., Sachidanandam, R. & Hannon, G. J. A role for microRNAs in maintenance of mouse mammary epithelial progenitor cells. *Genes Dev.* **21**, 3238-3243 (2007).

13. Ventura, A. *et al.* Cre-lox-regulated conditional RNA interference from transgenes. *Proc. Natl. Acad. Sci. U. S. A* **101**, 10380-10385 (2004).

14. Bouras, T. *et al.* Notch signaling regulates mammary stem cell function and luminal cell-fate commitment. *Cell Stem Cell* **3**, 429-441 (2008).

15. Dontu, G. *et al.* Role of Notch signaling in cell-fate determination of human mammary stem/progenitor cells. *Breast Cancer Res.* **6**, R605-R615 (2004).

16. Harrison, H. *et al.* Regulation of breast cancer stem cell activity by signaling through the Notch4 receptor. *Cancer Res.* **70**, 709-718 (2010).

17. Watters, J. W. *et al.* De novo discovery of a gamma-secretase inhibitor response signature using a novel in

vivo breast tumor model. *Cancer Res.* **69**, 8949-8957 (2009).

18. Laws, A. M. & Osborne, B. A. p53 regulates thymic Notch1 activation. *Eur. J. Immunol.* **34**, 726-734 (2004).

19 . Oswald, F. *et al.* p300 acts as a transcriptional coactivator for mammalian Notch-1. *Mol. Cell Biol.* **21**, 7761-7774 (2001).

20. Roperch, J. P. *et al.* Inhibition of presenilin 1 expression is promoted by p53 and p21WAF-1 and results in apoptosis and tumor suppression. *Nat. Med.* **4**, 835-838 (1998).

21. Giono, L. E. & Manfredi, J. J. The p53 tumor suppressor participates in multiple cell cycle checkpoints. *J. Cell Physiol* **209**, 13-20 (2006).

22. Green, D. R. & Chipuk, J. E. p53 and metabolism: Inside the TIGAR. *Cell* **126**, 30-32 (2006).

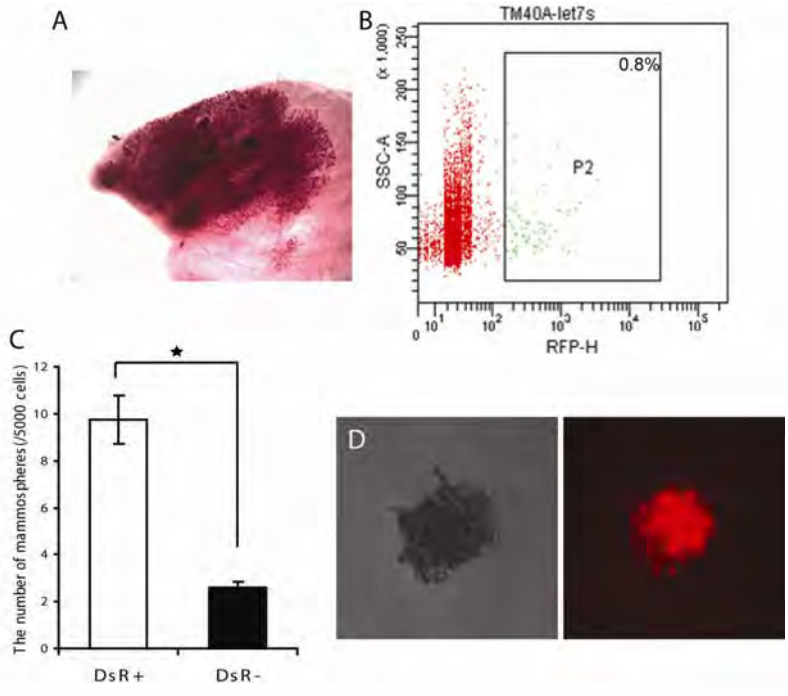
23. Green, D. R. & Kroemer, G. Cytoplasmic functions of the tumour suppressor p53. *Nature* **458**, 1127-1130 (2009).

24. Kleihues, P., Schauble, B., zur, H. A., Esteve, J. & Ohgaki, H. Tumors associated with p53 germline mutations: a synopsis of 91 families. *Am. J. Pathol.* **150**, 1-13 (1997).

25. Nichols, K. E., Malkin, D., Garber, J. E., Fraumeni, J. F., Jr. & Li, F. P. Germ-line p53 mutations predispose to a wide spectrum of early-onset cancers. *Cancer Epidemiol. Biomarkers Prev.* **10**, 83-87 (2001).

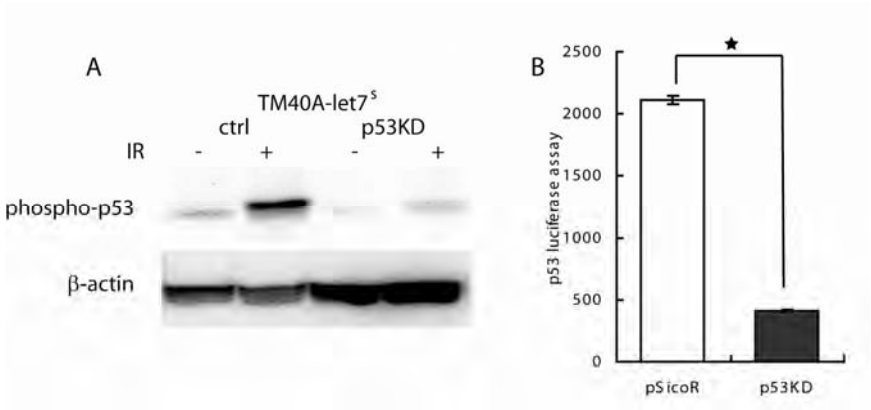
Supporting Data

Figure1.



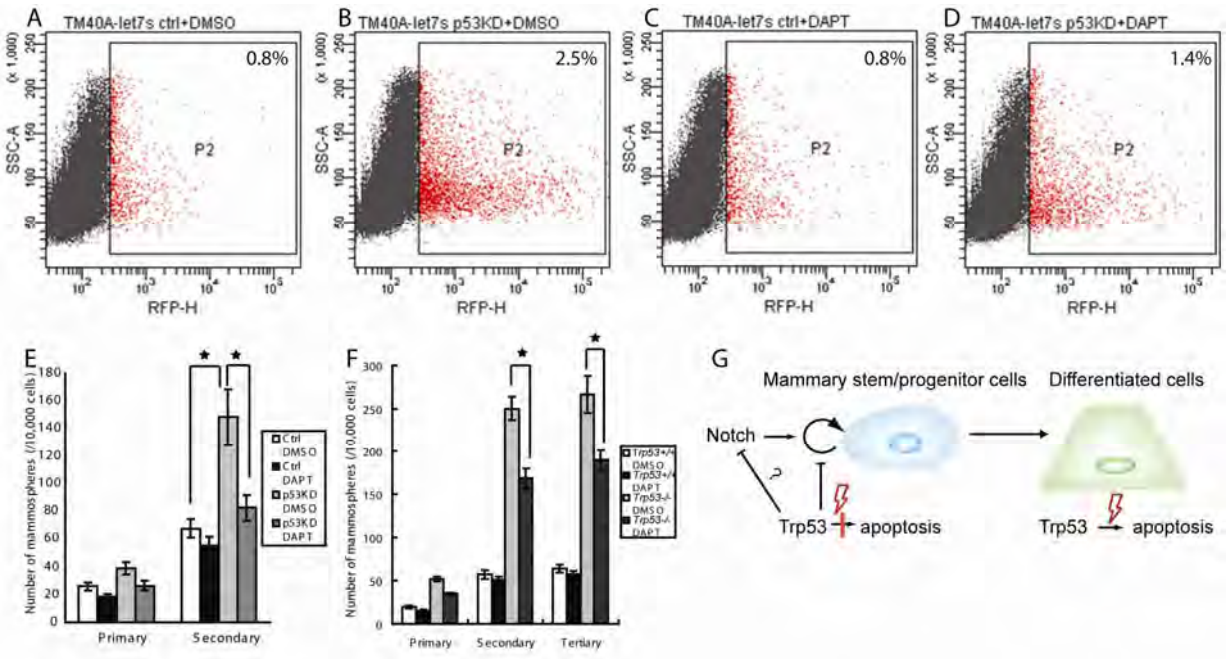
TM40A cells as an *in vitro* model to test the function of basal level p53. (A) Whole mount of a TM40A outgrowth 20 weeks after transplantation. (B) The let7c-sensor plasmid was introduced into TM40A cells (TM40A-let7^{s}). The TM40A-let7^{s} cells contained 0.8% of DsRed positive (Ds R^{+}) progenitor cells. Background levels of fluorescence were determined using control cells. (C) The DsR^{+} cells gave rise to significantly more mammospheres than DsR^{-} cells ($p<0.01$). (D) Most cells in the DsR^{+} mammospheres remained DsRed positive.

Figure2.



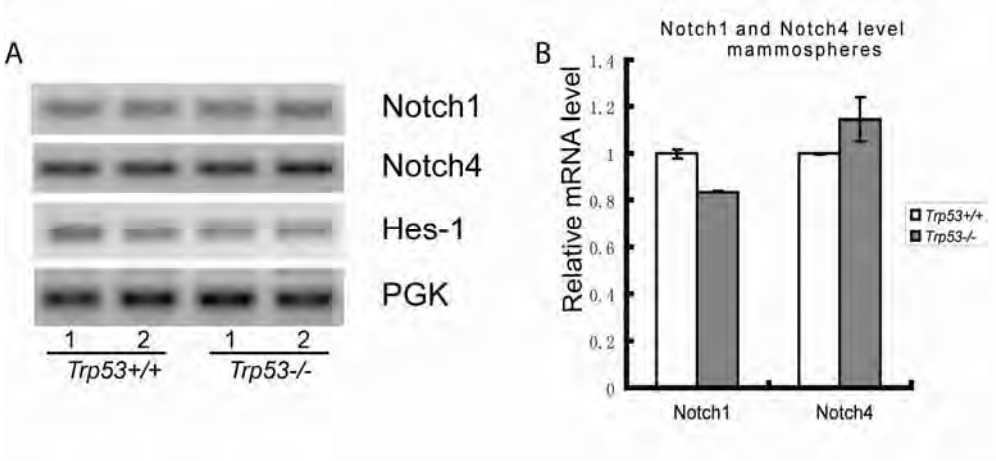
Knockdown of endogenous p53 using shRNA. (A) Western blot showed that phosphorylated p53 (phospho-p53) was reduced in TM40A-let7^{s}-p53KD cells compared to the control cells (TM40A-let7^{s}-ctrl). (B) Luciferase assay showed that the transactivation activity of basal level p53 was significantly reduced in TM40A-let7^{s}-p53KD compared to the control cells (pSicoR) ($p<0.01$).

Figure3.



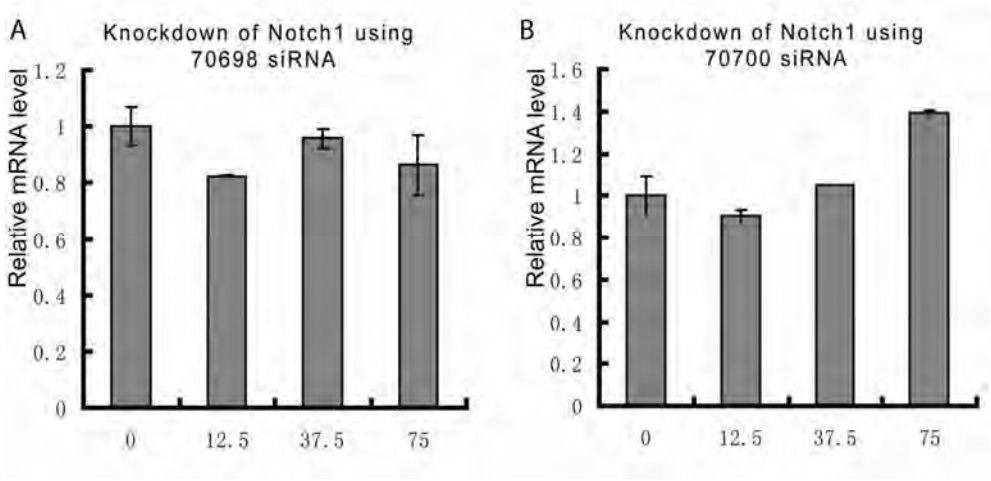
Inhibit the expansion of mammary stem/progenitor cells with γ-secretase inhibitor. (A-D) TM40A-let7^{s}-p53KD cells contained more DsR^{+} progenitor cells compared to the TM40A-let7^{s}-ctrl cells. The expansion of DsR^{+} progenitors in TM40A-let7^{s}-p53KD cells can be inhibited by the treatment of DAPT, while the DsR^{+} cells in TM40A-let7^{s}-ctrl cells were not affected. (E) TM40A-let7^{s}-p53KD cells gave rise to significantly more secondary mammospheres than control cells ($p<0.01$). The number of p53KD mammospheres decreased significantly with the treatment of 5 μM DAPT ($p<0.01$), while the number of control mammospheres were not affected ($p>0.05$). (F) Mammospheres were treated with either 5 μM DAPT or DMSO control during serial passages. The number of *Trp53-/-* mammospheres decreased significantly after the treatment of DAPT ($p<0.01$). The number of *Trp53+/+* mammospheres was not changed with DAPT treatment. (G) Model of p53 tumor suppression function in different cell types. p53 restricts the self-renewal of mammary stem/progenitor cells; however the p53-mediated apoptosis response is compromised in these cells. In the differentiated cells, the p53-mediated apoptosis pathway becomes functional. Notch may be inhibited by basal levels of p53 in mammary stem/progenitor cells. Insufficient p53 can result in increased Notch activity which leads to the expansion of mammary stem/progenitor cells.

Figure4.



Level of Notch pathway components in mammospheres of different genotypes. (A) Regular PCR showed no significant dif ference in the level of Notch1, Notch4 and Hes-1 between *Trp53+/+* and *Trp53-/-* m ammospheres. (B)Q PCR showed no significant dif ference in th e relative mRNA level of Notch1 and Notch4 between *Trp53+/+* and *Trp53-/-* mammospheres.

Figure 5.



Knockdown of Notch1 in TM40A cells using siRNA. (A, B) Either siRNA 70689 or 70700 effectively knocked down Notch1 in TM40A cells under recommended transfection condition.

Appendices

Manuscript: Repression of Mammary Stem/Progenitor Cells by p53 is Mediated by Notch and separable from Apoptotic Activity

STEM CELLS®

TISSUE-SPECIFIC STEM CELLS

Repression of Mammary Stem/Progenitor Cells by P53 is Mediated by Notch and Separable from Apoptotic Activity

Luwei Tao[1], Amy L. Roberts[2], Karen A. Dunphy[2,3], Carol Bigelow[4], Haoheng Yan[1], D. Joseph Jerry[1,2,3]

Author Affiliations: 1. Molecular and Cellular Biology Program, University of Massachusetts-Amherst, MA; 2. Department of Veterinary and Animal Science, University of Massachusetts-Amherst, MA; 3. Pioneer Valley Life Sciences Institute, Springfield, MA; 4. Division of Biostatistics and Epidemiology, University of Massachusetts-Amherst, MA

Key words. Tumor Suppressor Protein p53 • Li-Fraumeni Syndrome • Adult Stem Cells • Notch Proteins • apoptosis • Breast Neoplasms

ABSTRACT

Breast cancer is the most common tumor among women with inherited mutations in the p53 gene (Li-Fraumeni syndrome). The tumors represent the basal-like subtype which has been suggested to originate from mammary stem/progenitor cells. In mouse mammary epithelium, mammosphere-forming potential was increased with decreased dosage of the gene encoding the p53 tumor suppressor protein (*Trp53*). Limiting dilution transplantation also showed a 3.3-fold increase in the frequency of long-term regenerative mammary stem cells in *Trp53*-/- mice. The repression of mammospheres by p53 was apparent despite the absence of apoptotic responses to radiation indicating a dissociation of these two activities of p53. The effects of p53 on progenitor cells were also observed in TM40A cells using both mammosphere-forming assays and the DsRed-let7c-sensor. The frequency of long-term label-retaining epithelial cells (LRECs) was decreased in *Trp53*-/- mammary glands indicating that asymmetric segregation of DNA is diminished and contributes to the expansion of the mammary stem cells. Treatment with an inhibitor of γ-secretase (DAPT) reduced the number of *Trp53*-/- mammospheres to the level found in *Trp53*+/+ cells. These results demonstrate that basal levels of p53 restrict mammary stem/progenitor cells through Notch and that the Notch pathway is a therapeutic target to prevent expansion of this vulnerable pool of cells.

Author contributions: L.T.: Conception and design, collection and assembly of data, manuscript writing; A.R.: Other (technical support); K.D.: Other (technical support); C.B.: Data analysis and interpretation; H.Y.: Conception and design, collection and assembly of data; D.J.J.: Conception and design, manuscript writing, financial support, final approval of manuscript

Corresponding Author: D. Joseph Jerry, 661 North Pleasant Street, Integrated Science Building, Rm 427P, Department of Veterinary & Animal Sciences, University of Massachusetts Amherst, Amherst, MA 01003, Email: jjerry@vasci.umass.edu, Tel: 413-545-5335, Fax: 413-545-6326; Research Support: This work was supported by the Predoctoral Traineeship Award from Department of Defense Breast Cancer Research Program (W81XWH-09-1-0028 awarded to Luwei Tao) and funding from the National Institute of Health (R01-CA095164, R01-CA105452, R01-ES015739 awarded to Dr. D. Joseph Jerry). ; Received July 28, 2010; accepted for publication October 12, 2010. 1066-5099/2010/$30.00/0 doi: 10.1002/stem.552

INTRODUCTION

Mammary stem cells have been identified that are capable of regenerating the entire mammary ductal tree and repopulating the mammary fat pad [1, 2]. The mechanisms and pathways regulating self-renewal and differentiation of mammary stem cells are of great interest for its potential application in tissue replacement therapies as well as the prevention and treatment of breast cancer. The Wnt pathway was found to regulate the self-renewal of mammary stem/progenitor cells. Ectopic expression of Wnt1 resulted in an increased population of mammary stem/progenitor cells in the mammary gland and eventually induced mammary tumors [3]. Another breast cancer related gene, *BRCA1*, was reported to play a critical role in the differentiation of mammary stem/progenitor cells to luminal cells. Loss of both *BRCA1* alleles resulted in expansion of stem/progenitor cells in the breast epithelium of women and increased breast cancer risk [4]. The Notch pathway has also been implicated as regulator of mammary stem/progenitor cells self-renewal and differentiation but its function is controversial. Dontu et al reported that the activation of Notch signaling with DSL peptide resulted in 10-fold increase of mammosphere-forming activity [5]. Conversely, Bouras et al showed that the inhibition of Notch pathway by knockdown Cbf-1 in $CD29^{hi}CD24^{+}$ cells resulted in increased transplantation efficiency, suggesting that the Notch pathway may restrict mammary stem/progenitor cells expansion [6].

The p53 protein is a central regulator for multiple tumor suppressor pathways. The role of activated p53 in mediating cell cycle arrest and apoptosis has been studied extensively [7-9]. In response to DNA damage, oncogene activation or other stresses, p53 accumulates in nucleus and transactivates downstream genes, such as p21 and PUMA, and directs the fate of damaged cells resulting in repair or elimination [10, 11]. In addition to the importance of activated p53 under stress conditions, the basal level p53 under normal conditions may also play an essential role in tumor suppressor function. In both hematopoietic system and neural system, basal levels of p53 were shown to negatively regulate the self-renewal of tissue-specific stem cells [12, 13]. The *Arf-Trp53* pathway was shown to restrict the efficiency of reprogramming of induced pluripotent stem cells [14, 15].

Disruption of the gene encoding p53 (designated *TP53* in human and *Trp53* in mouse) predisposes normal mammary epithelium to tumorigenesis. Women with Li-Fraumeni syndrome, which is most commonly associated with germline heterozygous mutations of *TP53*, have significantly increased risk of breast cancer [16, 17]. Mutations and deletions of *TP53* are the most common alterations in cancers. The rate of p53 mutation is as high as 82% in the basal-like subtype of breast cancer, whereas in luminal A subtype, p53 mutations are found in only 13% patients suggesting that p53 mutation promotes basal-like breast cancer [18]. This class of aggressive tumors express gene signatures enriched in embryonic stem cells, and thus, have been proposed to originate from progenitor cells [19]. Mammary tumors from p53 heterozygous mouse models mimic Li-Fraumeni syndrome in women and the tumors share gene expression patterns with tumors from *Brca1*-deficient and Wnt1 transgenic mice and human basal-like breast cancer, suggesting that mammary tumors

from p53-deficient mice may also originate from the stem/progenitor cells [18, 20-22].

In this study, BALB/c-*Trp53*+/+, *Trp53*+/- and *Trp53*-/- mice were used to test the role of p53 in regulating the mammary stem/progenitor cells. We found that decreased p53 dosage resulted in increased frequency of mammary stem/progenitor cells, suggesting that basal levels of p53 inhibited self-renewal of mammary stem/progenitor cells. As the mammosphere-initiating cells of different *Trp53* genotypes were resistant to ionizing radiation (IR), p53-mediated apoptosis is comprised in these cells. Therefore, expansion of the mammary stem/progenitor cells population cannot be attributed to differences in apoptosis. Similarly, the decrease in the pool of label-retaining cells in *Trp53*-/- mammary epithelium also suggest that survival is not increased, but rather asymmetric segregation of DNA is diminished in the absence of p53 leading to dilution of the label during expansion of mammary stem/progenitor cells. We also showed that γ-secretase inhibitors (GSI) can be used to inhibit the expansion of *Trp53*-/- mammary stem/progenitor cells. The results demonstrate that p53 regulates self-renewal of mammary stem/progenitor cells and that insufficient basal levels of p53 can lead to expansion of the pool of mammary stem/progenitor cells, which are especially vulnerable to tumorigenesis without the proper surveillance of p53. Therefore, the Notch pathway is a potential therapeutic target to inhibit expansion of mammary stem/progenitor cells and reduce breast cancer risk.

MATERIALS AND METHODS

Animals

BALB/c-*Trp53*+/+, *Trp53*+/- and *Trp53*-/- mice were generated by backcrossing (C57BL/c x 129/Sv) *Trp53*-/- mice onto the BALB/cMed strain as described before [23]. Wild type 3 weeks old BALB/c recipient mice for transplantation were purchased from Jackson lab.

Isolation of primary mouse mammary cells

Mammary gland harvested from 8-10 weeks old virgin mice were minced and dissociated in DMEM:F12 (Sigma, St. Louis, MO) supplemented with 5% Fetal Bovine serum (Gibco, Paisley, UK), 2mg/ml collagenase (Worthington Biochemicals, Freehold, NJ), 100u/ml hyaluronidase (Sigma), 100u/ml pen/strep (Gibco) and 100 μg/ml gentamicin (Gibco) for 6 hours. The cell pellet was collected and further dissociated with 1ml pre-warmed 0.05% Trypsin-EDTA (Gibco) and 200μl 1mg/ml DNase I (Roche, Mannheim, Germany). Cell suspensions were sieved through a 40μm cell strainer to obtain single cell suspension.

Mammosphere culture

Primary single cells were seeded into ultra-low attachment dishes or plates at a density of 20,000 viable cells/ml. Cells were grown in a serum-free mammary epithelial growth medium (HuMEC, Gibco) supplemented with B27 (Gibco), 20ng/ml EGF (Sigma), 20ng/ml bFGF (Sigma), 4μg/ml heparin (Sigma), 100u/ml Pen/Strep, 5μg/ml gentamicin [24]. For the GSI treatment, N-[N-(3,5-Difluorophenacetyl)-L-alanyl]-S-phenylglycine t-butyl ester (DAPT, Sigma) was added into culture medium to the final concentration of 5μM (final DMSO concentration 0.1%). To passage mammospheres, mammospheres were collected with gentle centrifugation 800rpm for

5min 7 days after culture and dissociated with 1ml pre-warmed 0.05%Trypsin-EDTA and 60μl 1mg/ml DNase I for 5-8min. Cell suspensions obtained from dissociation were sieved through 40μm cell strainer and seeded at a density of 1,000 viable cells/ml. To test the IR responses of mammosphere-initiating cells, single cell suspensions received 0-Gy (control group) or 5-Gy dose (radiation group) of γ-irradiation from a cesium-137 source before being plated.

Limiting dilution and transplantation

Primary mammary epithelial cells (MECs) were freshly isolated as described above and resuspended in DMEM:F12 with 5%FBS. Six different cell concentrations were used: 50,000/10μl, 10,000/10μl, 5,000/10μl, 2,500/10μl, 1,000/10μl, 100/10μl. *Trp53+/+* cell suspensions were injected into right side of #4 cleared fat pads of 3 weeks old recipient mice and the same concentration of *Trp53-/-* cell suspensions were injected into the contralateral left side fat pad. The transplanted fat pads were harvested and stained with Carmine Alum solution 8 weeks after transplantation [25]. Outgrowths that occupied >5% of the fat pad were regarded as a successful outgrowth [26]. Two methods were used to estimate the frequency of long-term regenerative mammary stem cells. The L-Calc software (Stemcell Tech, Vancouver, Canada) has been reported previously [27]. We also used a generalized linear model approach assuming an underlying Poisson distribution of stem cell frequency to model the limiting dilution data using Stata (Stata Corp, College Station, TX). The regression model included a term for the multiplicative effect of *Trp53+/+* (relative to *Trp53-/-*) and model adequacy was assessed using the link test. The Wilcoxon signed-rank test was used to compare the percentage of filled fat pad between *Trp53+/+* and *Trp53-/-* epithelium. The model was not adjusted for the paired design where *Trp53+/+* and *Trp53-/-* transplants are tested within each animal. The paired design would bias results in the direction of the null hypothesis resulting in a conservative estimate of statistically significant findings.

TM40A cell culture and retroviral infection

TM40A cells were maintained in regular MECL media: DMEM:F12 supplemented with 2% adult bovine serum (Gibco), 10μg/ml Insulin (Sigma), 20ng/ml mEGF, and 100u/ml Pen/Strep. Oligos coding for the p53 knockdown or scramble shRNA were annealed and cloned into pSicoR-PGK-puro vector (Addgene, Cambridge, MA). The p53 target sequence was GTACTCTCCTCCCCTCAAT and the scramble sequence was CGCTACACACTTCTTCTCC. The infection of TM40A cells with let-7c sensor plasmid, pSicoR-PGK-puro-p53KD plasmid or the control plasmids were performed as described previously [28, 29].

Flow cytometry and cell sorting

Cells were freshly collected and resuspended in DMEM:F12 supplemented with 1mM EDTA, 25mM HEPES, 1%FBS and 100u/ml Pen/Strep. The FACS data were collected using LSRII (Becton Dickinson, San Jose CA). A total 100,000 events were collected and analyzed using BD FACSDiva software (Becton Dickinson). Cell sorting was performed using a FACSVantage SE (Becton Dickinson).

Western blot

TM40A cell protein lysates were harvested 1 hour after 0-Gy or 10-Gy of γ-irradiation using RIPA buffer (50mM Tris, 150mM NaCl, 1% TritonX-100, 10% glycerol, 0.1% SDS, 0.5% deoxycholate, 1x protease inhibitor (Sigma, p8340) and 1x phosphatase inhibitor (Sigma,

P5726)). Protein lysates (80μg) were separated by 10% SDS-PAGE and transferred to PVDF membrane (Millipore, Billerica, MA). The membrane was incubated with anti-phospho p53 (1:1000, Cell Signaling, 9284), or anti-β-actin (1:4000, Sigma, A1978), followed by incubation with hoseradish peroxidase conjugated secondary antibodies (1:5000, GE Healthcare, Little Chalfont, Buckinghamshire, UK), and developed using enhanced chemiluminescence (ECL) solution (GE Healthcare) in G:Box imaging system (Syngene, Cambridge, UK).

Label retaining cells

3 weeks old BALB/c-*Trp53*+/+ and BALB/c-*Trp53*-/- mice were injected with BrdU (Sigma) 300μg/10g body weight for 7 days. Mammary glands were harvested 9 weeks after the final injection. 5 *Trp53*+/+ mice and 3 *Trp53*-/- mice were used in this experiment. BrdU staining was done using the BrdU staining kit (Invitrogen, Carlsbad, CA) and the whole slides were counted for the total epithelial cells and LRECs.

RESULTS

p53 inhibits the expansion of mammary stem/progenitor cells

In order to examine the effect of p53 on mammary stem/progenitor cells, mammosphere formation capacity was compared among BALB/c-*Trp53*+/+, *Trp53*+/- and *Trp53*-/- mice. During serial passages, *Trp53*-/- epithelial cells gave rise to significantly higher numbers of secondary and tertiary mammospheres than wild type epithelium ($p<0.01$) (Fig. 1A), suggesting that p53 restricts expansion of mammary stem/progenitor cells. *Trp53*+/- epithelium also gave rise to higher numbers of mammmospheres than *Trp53*+/+, indicating the importance of p53 dosage with respect to regulation of mammary stem/progenitor cells. Furthermore, the *Trp53*-/- mammospheres are also larger than *Trp53*+/+ mammospheres, suggesting more extensive proliferation (Fig. 1B).

To estimate the frequency of long-term regenerative mammary stem cells, we performed limiting dilution and transplantation to test the ability of cells to reconstitute the mammary gland. Total mammary cells were isolated from 8-10 week old aged-matched BALB/c-*Trp53*+/+ and *Trp53*-/- donor mice. The cells were transplanted into cleared mammary fat pads of 3-week old wild type BALB/c recipients. Both *Trp53*+/+ and *Trp53*-/- outgrowths showed normal ductal structure in both whole mounts (Fig.1 D, F) and HE staining (Fig.1 E, G). Using L-Calc Software, the frequency of mammary stem cell in BALB/c-*Trp53*+/+ epithelium was estimated to be 1 in 8,085 (± 1S.E. 6,508 - 10,045) compared to 1 in 2,445 (± 1S.E. 2,033 - 2,940) in BALB/c-*Trp53*-/- epithelium (Fig. 1C, H). The frequency of long-term regenerative mammary stem cells in *Trp53*-/- epithelium was 3.3-fold higher than the *Trp53*+/+ epithelium ($p<0.001$), suggesting that basal levels of p53 inhibits the expansion of mammary stem cells and that insufficient p53 dosage results in increased numbers of mammary stem cells between these genotypes. A generalized linear model approach was also applied and produced similar estimates of the difference in frequency of mammary stem cells. It is also noticeable that *Trp53*-/- outgrowths occupied a significantly higher percentage of the gland than the *Trp53*+/+ outgrowth ($p<0.01$), suggesting increased regenerative capacity of the *Trp53*-/- mammary stem cells (Fig. 1H).

p53-mediated apoptosis pathway is compromised in mammary stem/progenitor cells

Ionizing radiation (IR) causes DNA double strand breaks, which induces preferentially p53-dependent cell cycle arrest and apoptosis. To test whether the different number of mammospheres may be an artifact of defective apoptosis in *Trp53*-/- cells, we used IR to trigger DNA damage and apoptosis. Upon serial passages, mammosphere cell suspensions were treated with either 0-Gy or 5-Gy γ-irradiation then seeded in parallel. Surprisingly, the number of secondary or tertiary mammospheres was not affected by IR in any of the genotypes ($p>0.05$) (Fig. 2A, B), suggesting that the mammosphere-initiating cells are resistant to IR and that the p53-mediated apoptosis pathway is compromised in these cells. These results indicate that the increase in mammary stem/progenitor cells is not attributed to differences in apoptosis or survival in *Trp53-/-* cells and that p53 acts by a distinct mechanism to limit the mammary stem/progenitor cells.

***Trp53-/-* mammary epithelium contained fewer label retaining epithelial cells (LRECs)**

Non-random segregation of chromatids was reported in both embryonic stem cells and multilineage progenitor cells [30]. It has been postulated that the tissue specific stem cells maintain their "stemness" and protect themselves from mutation through asymmetric segregation of their template DNA strands [31, 32]. LRECs have been reported in mammary gland by using either [^{3}H]-thymidine or BrdU labeling [33]. We labeled BALB/c-*Trp53*+/+ and *Trp53-/-* mice with BrdU when 3 weeks old and chased for 9 weeks. Both genotypes exhibited similar incorporation of BrdU immediately after the labeling period. After 9 weeks of chasing, the BrdU-retaining epithelial cells were found in both luminal and basal compartments and the distribution of LRECs was similar among both genotypes (Fig. 3A, B). However, *Trp53-/-* mammary glands contained significantly fewer LRECs (1.26±0.09%) than the *Trp53*+/+ mammary glands (2.56±0.18%) ($p<0.01$, Fig. 3C), indicating that asymmetric segregation of DNA is impaired in the absence of p53 resulting in dilution of the BrdU label.

TM40A cells as an *in vitro* model to test the function of basal level p53

The role of p53 in regulation of mammary stem/progenitor cells was further confirmed *in vitro* using the TM40A cell line, a mammary epithelial cell line derived from BALB/c mice and retains wild type p53 mRNA (unpublished data, DJJ). TM40A cells form hyperplastic outgrowths when transplanted *in vivo* (Fig. 4A) but have undetectable tumorigenicity through 20 weeks. The let-7 microRNA family was shown to be depleted in the mammary progenitor cells and highly expressed in the more differentiated cell types and the let-7c sensor plasmid (let7^s) has been used to label mammary progenitor population *in vitro* [28]. The TM40A-let7^s cells contained 0.8% of DsRed positive (DsR$^+$) progenitor cells (Fig. 4B). The mammosphere-forming capacity of DsR$^+$ cells is 3.8-fold greater than DsR$^-$ cells ($p<0.01$) (Fig. 4C), confirming their progenitor feature. Interestingly, most of the cells in the DsR$^+$ mammospheres remained DsR$^+$ (Fig. 4D).

We proceeded to determine whether the knockdown of p53 can change the proportion of DsR$^+$ progenitor cells. TM40A-let7^s cells were infected with a p53 shRNA plasmid (TM40A-let7^s-p53KD) or control plasmid (TM40A-let7^s-ctrl) as described previously [29].

The p53 shRNA decreased p53 protein to less than 24% of the original level (Fig. 4E). The TM40A-let7^{s}-p53KD contained increased numbers of DsR^{+} cells (2.5%) compared to the TM40A-let7^{s}-ctrl cells (0.8%) (Fig. 5A and B). The number of secondary mammospheres formed by TM40A-let7^{s}-p53KD cells was also 2.2-fold higher than the control cells ($p<0.01$) (Fig. 5E), further proving that the basal level of p53 inhibits the expansion of mammary progenitor cells.

Notch inhibitor reduced the number of mammary stem/progenitor cells

Increased mammary stem/progenitor cells could be vulnerable targets for carcinogenesis, especially in Li-Fraumeni patients in whom p53-mediated genome surveillance is compromised. We proceeded to test the potential of pharmacological methods to inhibit the expansion of mammary stem/progenitor cells. The Notch pathway has been reported to both promote and limit progenitor cells [5, 6], therefore we tested whether γ-secretase inhibitors (GSI), could affect the expansion of p53-deficient mammary stem/progenitor cells. The number of TM40A-let7^{s}-p53KD mammospheres decreased to baseline levels after the treatment with DAPT, a GSI (Fig. 5E; $p<0.01$) indicating that Notch pathway could be a potential therapeutic target for downregulation of mammary stem/progenitor cells. The number of mammospheres in control cells with wild type p53 was not changed with DAPT treatment showing that inhibition of Notch was not a general effect, but specifically reversed the effect of p53-deficiency (Fig. 5E). DAPT treatment also restricted the expansion of progenitors measured by DsR^{+} sensor after p53 knockdown. In TM40A-let7^{s}-p53KD cells, DAPT decreased the DsR^{+} cells from 2.5% to 1.4% (compare Fig. 5B and D), whereas the proportion of DsR^{+} cells was not changed by DAPT in the control group (compare Fig.5A and C). *Trp53-/-* and *Trp53+/+* primary mammary epithelial cells were also treated with 5μM DAPT or DMSO. Similarly, DAPT significantly inhibited the expansion of *Trp53-/-* mammospheres. The number of *Trp53-/-* secondary mammospheres decreased significantly from 250±13/10,000 cells to 168±11/10,000 cells after the DAPT treatment ($p<0.01$), but the number of *Trp53+/+* mammospheres were not affected (Fig. 5F).

DISCUSSION

The importance of p53 in breast cancer is highlighted by the dramatic increase of breast cancer risk among women with Li-Fraumeni syndrome [16, 17]. Although the function of activated p53 in mammary epithelium has been extensively studied, its role at basal levels under normal conditions is not fully understood. Both the mammosphere and limiting dilution data showed that insufficient basal levels of p53 resulted in increased numbers of mammary stem/progenitor cells. A gene dosage effect was also detected with the frequency of mammosphere-forming activity being intermediate for *Trp53+/-* mammary epithelium compared to the *Trp53+/+* and *Trp53-/-*.

Label-retaining cell assays provide a measure of the asymmetric divisions of stem cells. Smith *et al* reported that by using [^{3}H]-thymidine as the first label for LRECs and BrdU as secondary label for recently proliferating cells, most LRECs were actively synthesizing DNA yet retained their [^{3}H]-thymidine labeled strands, suggesting that asymmetrically dividing cells contribute to most of LRECs [33]. Organ specific stem cells could also be static and divide less frequently, which may also contribute to their label-retaining

feature [31, 34]. Recently, reports showed that p53 is essential for maintaining quiescence of mammary stem cells as well as hematopoietic stem cells [34, 35]. In our experiment, the frequency of LRECs in wild type mice was 2.56±0.18%, which is close to that reported by Smith *et al* using [^{3}H]-thymidine. We showed that *Trp53-/-* epithelium contained fewer LRECs than wild type epithelium. This could be explained by increased proliferation of *Trp53-/-* mammary stem cells, which dilute the BrdU after 9 weeks of chasing. Alternatively, p53 may regulate the asymmetric segregation of sister chromatids during mitosis, which could be vital for the fate decision of daughter cells. Loss of p53 may result in the disruption of this asymmetric segregation, leading to the loss of BrdU labeling after several rounds of division.

As p53 plays a prominent role in apoptosis, it was possible that differences in cell survival could contribute to the apparent increase in mammary stem/progenitor cells. However, radiation treatment failed to alter the number of secondary or tertiary mammospheres in any *Trp53* genotype suggesting that p53-mediated apoptosis is compromised in the mammary stem/progenitor cell population. Previous studies have also demonstrated the resistance of mammary progenitors to therapeutic doses of ionizing radiation [36, 37]. Furthermore, if differences in apoptosis were responsible for the apparent expansion of mammary stem/progenitor cells, the frequency of LRECs would be expected to be increased, but were in fact decreased significantly. Therefore, the expansion of mammary stem/progenitor cells cannot be attributed to altered survival of p53-deficient cells.

These results highlight the disparate functions and roles of p53 in different cell types. It was reported that ES cells could not activate p53-dependent responses to ionizing radiation because p53 protein was sequestered in the cytoplasm [38]. Nonetheless, under basal conditions p53 was found to suppress expression of Nanog and induce differentiation of mouse ES cells [39]. In mammary gland, irradiation triggers p53-mediated apoptosis in ductal epithelium [40], but this surveillance activity of p53 was not detectable in mammary stem/progenitor cells (Fig. 2). Nonetheless, the ability of basal levels of p53 to restrict the pool of progenitors was retained (Fig. 1). Therefore, the tumor suppressor function of p53 can be divided into two different aspects. In differentiated cells, p53 can be activated due to various genotoxic or cellular stresses so that the damaged cells will either be repaired or eliminated through apoptosis, depending on the extent of damage. In contrast, the apoptosis-inducing function of p53 is compromised in the mammary stem/progenitor cells, which prevents the loss of tissue-specific stem cells and the premature aging process due to DNA damage or other cellular challenges. In these cells, the major tumor suppressor function of p53 is to restrict self-renewal and inhibit inappropriate expansion of mammary stem/progenitor cells, a function that is independent of the pro-apoptotic function of p53 (Fig. 5G).

The elucidation of mammary stem cells and breast cancer stem cells has stimulated greatly the discussion of the cellular origins of breast cancers [21, 41]. In small intestine, the deletion of the adenomatosis polyposis coli gene (*Apc*) in intestinal stem cells showed much higher transformation efficiency than in short-lived transit-amplifying cells, providing direct

evidence of the stem cell origin of intestinal cancer [42]. In mammary gland, the complexity of breast cancer subtypes and mammary epithelial cell hierarchy makes it hard to identify the cellular origins of breast cancer. Type I human breast epithelial cells (HBECs) express features of luminal stem/progenitor cells and show a greater potential for immortalization and transformation by oncogenes [43-45]. The pathologic features of tumors also appear to differ among populations sequentially immortalized and transformed with TERT, SV40-T-antigen and activated Ras [46]. These observations suggest that the mammary stem/progenitor cells are sensitive to oncogenic transformation, although the possibility of transformation of differentiated epithelial cells can not be ruled out. Therefore, modest increases in the prevalence of stem/progenitor cells would be anticipated to increase risk of breast cancer and are a likely source of cancer stem cells.

Germline heterozygous mutations in *TP53* or *BRCA1* significantly increase breast cancer risk. *BRCA1* was also shown to regulate self-renewal and cell fate decision of mammary stem/progenitor cells. Loss of heterozygosity (LOH) of *BRCA1* resulted in histologically normal lobules, which are comprised of progenitor cells and have higher transformation risk [4]. Similarly, loss of p53 function is associated with basal-like breast cancers that express markers of embryonic stem cells [18, 19]. Mammary tumors from p53-deficient mouse models also appear to develop from bipotent progenitor cells and have gene expression patterns similar to embryonic stem cells [22, 41]. Our lab showed that 62% of spontaneous mammary tumors from *Trp53+/-* mice contained mixture of cells expressing either K5 or K8/18 [22]. It is likely that the expansion of mammary stem/progenitor cells resulting from loss of p53 activity contributes to the great breast cancer risk due to their long life span and the ability to give rise to multiple lineages of differentiated cells. Therefore the inhibition of mammary stem/progenitor cell expansion may be a key target for prevention of hereditary breast cancers.

Expression of Notch pathway members were especially prominent in the gene expression patterns in mammary tumors of p53-deficient mice [22] suggesting that this pathway may contribute to the expansion of mammary stem/progenitor cells. We found that treatment of *Trp53-/-* primary cells and TM40A-let7^{s}-p53KD cells with DAPT significantly downregulated the mammosphere-forming activity and the number of DsR^{+} progenitor cells. However DAPT did not change the mammosphere number of *Trp53+/+* or TM40A-let7^{s}-ctrl cells. This data agreed with the report of Dontu *et al*, which demonstrated that the Notch pathway upregulated the number of mammary stem/progenitor cells [5]. The p53 protein has been reported to inhibit activation of the Notch pathway at different levels by either inhibiting the transcription of presenilin-1 (PS1) or competing with Notch-1 intracellular domain for co-activator p300/CBP [47-49]. Similar mechanisms may lead to the inhibition of Notch pathway by p53 in mammary stem/progenitor cells. In the absence of p53, this inhibition is released, which allows expansion of mammary stem/progenitor cells. While in the presence of p53, the inhibition mechanism is intact and the treatment of DAPT did not affect the self-renewal of mammary stem/progenitor cells (Fig. 5G). Researchers have tried to apply GSI on breast cancer treatment and showed that GSI is effective in suppression of breast cancer stem cells and inhibition of breast cancer growth [50, 51]. The GSI-sensitive signature suggested that pathways,

including the Notch pathway and chemokine signaling pathway may contribute to the sensitivity of breast cancer to GSI [51]. However, it remains possible that other targets of γ-secretase are important. Our results suggest that the Notch pathway is a potential therapeutic target to inhibit the expansion of mammary stem/progenitor cells and GSI may be applied to prevent breast cancer in patients with Li-Fraumeni syndrome.

SUMMARY

Proper regulation of the pool of progenitor cells is increasingly recognized as a factor in determining risk of breast cancer. We show that decreased p53 gene dosage results in increased numbers of progenitor cells through a mechanism that involves loss of asymmetric divisions and apparent increases in Notch activity, but not alterations in apoptosis. Inhibition of Notch signaling with a γ-secretase inhibitor reversed the effect of p53 loss resulting in restriction of the number of mammary stem/progenitor cells. As inhibition of Notch limited the pool of mammary stem/progenitor cells in p53-deficient mammary epithelium but had no effect in *Trp53*+/+ cells, it appears to be an effective treatment to prevent mammary tumors due to loss of p53 function with minimal consequences to cells with wild type p53.

ACKNOWLEDGMENTS

We thank Dr. Daniel Medina for inspiring critiques and background information on TM40A cells, Dr. Gregory Hannon for the gift of let7c-sensor and control plasmids.

Disclosure of Potential Conflicts of Interest

The authors indicate no potential conflicts of interest.

REFERENCES

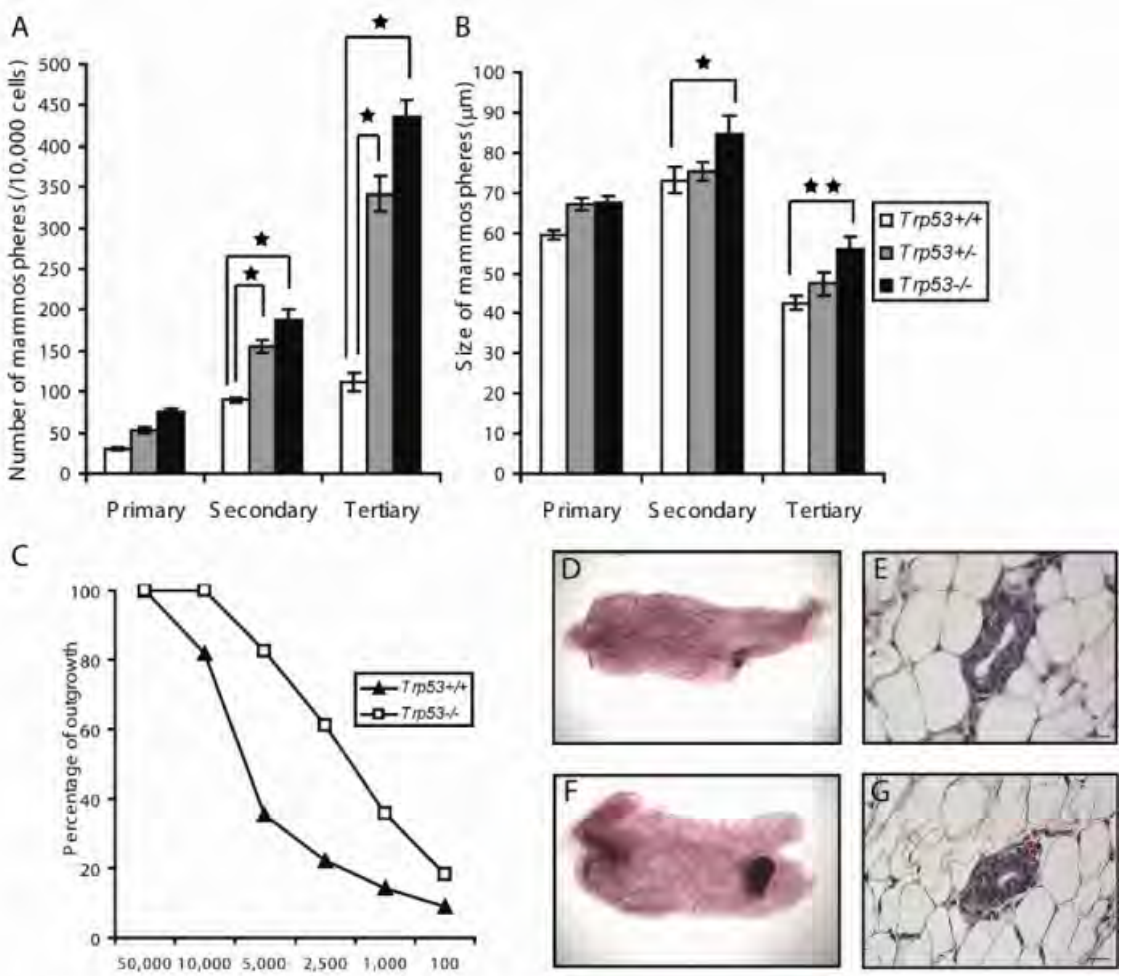
1. Shackleton M, Vaillant F, Simpson KJ et al. Generation of a functional mammary gland from a single stem cell. NATURE 2006;439(7072):84-88.
2. Stingl J, Eirew P, Ricketson I et al. Purification and unique properties of mammary epithelial stem cells. NATURE 2006;439(7079):993-997.
3. Li Y, Welm B, Podsypanina K et al. Evidence that transgenes encoding components of the Wnt signaling pathway preferentially induce mammary cancers from progenitor cells. PROC. NATL. ACAD. SCI. U. S. A 2003;100(26):15853-15858.
4. Liu S, Ginestier C, Charafe-Jauffret E et al. BRCA1 regulates human mammary stem/progenitor cell fate. PROC. NATL. ACAD. SCI. U. S. A 2008;105(5):1680-1685.
5. Dontu G, Jackson KW, McNicholas E et al. Role of Notch signaling in cell-fate determination of human mammary stem/progenitor cells. BREAST CANCER RES. 2004;6(6):R605-R615.
6. Bouras T, Pal B, Vaillant F et al. Notch signaling regulates mammary stem cell function and luminal cell-fate commitment. CELL STEM CELL 2008;3(4):429-441.
7. Giono LE, Manfredi JJ. The p53 tumor suppressor participates in multiple cell cycle checkpoints. J. CELL PHYSIOL 2006;209(1):13-20.
8. Zhivotovsky B, Kroemer G. Apoptosis and genomic instability. NAT. REV. MOL. CELL BIOL. 2004;5(9):752-762.
9. Rohaly G, Chemnitz J, Dehde S et al. A novel human p53 isoform is an essential element of the ATR-intra-S phase checkpoint. CELL 2005;122(1):21-32.

10. Jimenez GS, Khan SH, Stommel JM et al. p53 regulation by post-translational modification and nuclear retention in response to diverse stresses. ONCOGENE 1999;18(53):7656-7665.
11. Murray-Zmijewski F, Slee EA, Lu X. A complex barcode underlies the heterogeneous response of p53 to stress. NAT. REV. MOL. CELL BIOL. 2008;9(9):702-712.
12. Dumble M, Moore L, Chambers SM et al. The impact of altered p53 dosage on hematopoietic stem cell dynamics during aging. BLOOD 2007;109(4):1736-1742.
13. Meletis K, Wirta V, Hede SM et al. p53 suppresses the self-renewal of adult neural stem cells. DEVELOPMENT 2006;133(2):363-369.
14. Li H, Collado M, Villasante A et al. The Ink4/Arf locus is a barrier for iPS cell reprogramming. NATURE 2009;460(7259):1136-1139.
15. Hong H, Takahashi K, Ichisaka T et al. Suppression of induced pluripotent stem cell generation by the p53-p21 pathway. NATURE 2009;460(7259):1132-1135.
16. Kleihues P, Schauble B, zur HA et al. Tumors associated with p53 germline mutations: a synopsis of 91 families. AM. J. PATHOL. 1997;150(1):1-13.
17. Nichols KE, Malkin D, Garber JE et al. Germ-line p53 mutations predispose to a wide spectrum of early-onset cancers. CANCER EPIDEMIOL. BIOMARKERS PREV. 2001;10(2):83-87.
18. Sorlie T, Perou CM, Tibshirani R et al. Gene expression patterns of breast carcinomas distinguish tumor subclasses with clinical implications. PROC. NATL. ACAD. SCI. U. S. A 2001;98(19):10869-10874.
19. Ben-Porath I, Thomson MW, Carey VJ et al. An embryonic stem cell-like gene expression signature in poorly differentiated aggressive human tumors. NAT. GENET. 2008;40(5):499-507.
20. Herschkowitz JI, Simin K, Weigman VJ et al. Identification of conserved gene expression features between murine mammary carcinoma models and human breast tumors. GENOME BIOL. 2007;8(5):R76.
21. Stingl J, Caldas C. Molecular heterogeneity of breast carcinomas and the cancer stem cell hypothesis. NAT. REV. CANCER 2007;7(10):791-799.
22. Yan H, Blackburn AC, McLary SC et al. Pathways Contributing to Development of Spontaneous Mammary Tumors in BALB/c-Trp53+/- Mice. AM. J. PATHOL. 2010.
23. Jerry DJ, Kittrell FS, Kuperwasser C et al. A mammary-specific model demonstrates the role of the p53 tumor suppressor gene in tumor development. ONCOGENE 2000;19(8):1052-1058.
24. Dontu G, Abdallah WM, Foley JM et al. In vitro propagation and transcriptional profiling of human mammary stem/progenitor cells. GENES DEV. 2003;17(10):1253-1270.
25. Susan B.Rasmussen, Lawrence J.T.Young, Gilbert H.Smith. Preparing mammary gland whole mounts from mice. In: Margot M.Ip, Bonnie BA, eds, 2000.
26. Siwko SK, Dong J, Lewis MT et al. Evidence that an early pregnancy causes a persistent decrease in the number of functional mammary epithelial stem cells--implications for pregnancy-induced protection against breast cancer. STEM CELLS 2008;26(12):3205-3209.
27. Britt KL, Kendrick H, Regan JL et al. Pregnancy in the mature adult mouse does not alter the proportion of mammary epithelial stem/progenitor cells. BREAST CANCER RES. 2009;11(2):R20.
28. Ibarra I, Erlich Y, Muthuswamy SK et al. A role for microRNAs in maintenance of mouse mammary epithelial progenitor cells. GENES DEV. 2007;21(24):3238-3243.
29. Ventura A, Meissner A, Dillon CP et al. Cre-lox-regulated conditional RNA interference from transgenes. PROC. NATL. ACAD. SCI. U. S. A 2004;101(28):10380-10385.
30. Armakolas A, Klar AJ. Cell type regulates selective segregation of mouse chromosome 7 DNA strands in mitosis. SCIENCE 2006;311(5764):1146-1149.
31. Wilson A, Laurenti E, Oser G et al. Hematopoietic stem cells reversibly switch from dormancy to self-renewal

during homeostasis and repair. CELL 2008;135(6):1118-1129.

32. Shinin V, Gayraud-Morel B, Gomes D et al. Asymmetric division and cosegregation of template DNA strands in adult muscle satellite cells. NAT. CELL BIOL. 2006;8(7):677-687.
33. Smith GH. Label-retaining epithelial cells in mouse mammary gland divide asymmetrically and retain their template DNA strands. DEVELOPMENT 2005;132(4):681-687.
34. Cicalese A, Bonizzi G, Pasi CE et al. The tumor suppressor p53 regulates polarity of self-renewing divisions in mammary stem cells. CELL 2009;138(6):1083-1095.
35. Liu Y, Elf SE, Miyata Y et al. p53 regulates hematopoietic stem cell quiescence. CELL STEM CELL 2009;4(1):37-48.
36. Chen MS, Woodward WA, Behbod F et al. Wnt/beta-catenin mediates radiation resistance of Sca1+ progenitors in an immortalized mammary gland cell line. J. CELL SCI. 2007;120(Pt 3):468-477.
37. Woodward WA, Chen MS, Behbod F et al. WNT/beta-catenin mediates radiation resistance of mouse mammary progenitor cells. PROC. NATL. ACAD. SCI. U. S. A 2007;104(2):618-623.
38. Aladjem MI, Spike BT, Rodewald LW et al. ES cells do not activate p53-dependent stress responses and undergo p53-independent apoptosis in response to DNA damage. CURR. BIOL. 1998;8(3):145-155.
39. Lin T, Chao C, Saito S et al. p53 induces differentiation of mouse embryonic stem cells by suppressing Nanog expression. NAT. CELL BIOL. 2005;7(2):165-171.
40. Dunphy KA, Blackburn AC, Yan H et al. Estrogen and progesterone induce persistent increases in p53-dependent apoptosis and suppress mammary tumors in BALB/c-Trp53+/- mice. BREAST CANCER RES. 2008;10(3):R43.
41. Zhang M, Behbod F, Atkinson RL et al. Identification of tumor-initiating cells in a p53-null mouse model of breast cancer. CANCER RES. 2008;68(12):4674-4682.
42. Barker N, Ridgway RA, van Es JH et al. Crypt stem cells as the cells-of-origin of intestinal cancer. NATURE 2009;457(7229):608-611.
43. Kao CY, Nomata K, Oakley CS et al. Two types of normal human breast epithelial cells derived from reduction mammoplasty: phenotypic characterization and response to SV40 transfection. CARCINOGENESIS 1995;16(3):531-538.
44. Chang CC, Sun W, Cruz A et al. A human breast epithelial cell type with stem cell characteristics as target cells for carcinogenesis. RADIAT. RES. 2001;155(1 Pt 2):201-207.
45. Sun W, Kang KS, Morita I et al. High susceptibility of a human breast epithelial cell type with stem cell characteristics to telomerase activation and immortalization. CANCER RES. 1999;59(24):6118-6123.
46. Ince TA, Richardson AL, Bell GW et al. Transformation of different human breast epithelial cell types leads to distinct tumor phenotypes. CANCER CELL 2007;12(2):160-170.
47. Laws AM, Osborne BA. p53 regulates thymic Notch1 activation. EUR. J. IMMUNOL. 2004;34(3):726-734.
48. Oswald F, Tauber B, Dobner T et al. p300 acts as a transcriptional coactivator for mammalian Notch-1. MOL. CELL BIOL. 2001;21(22):7761-7774.
49. Roperch JP, Alvaro V, Prieur S et al. Inhibition of presenilin 1 expression is promoted by p53 and p21WAF-1 and results in apoptosis and tumor suppression. NAT. MED. 1998;4(7):835-838.
50. Harrison H, Farnie G, Howell SJ et al. Regulation of breast cancer stem cell activity by signaling through the Notch4 receptor. CANCER RES. 2010;70(2):709-718.
51. Watters JW, Cheng C, Majumder PK et al. De novo discovery of a gamma-secretase inhibitor response signature using a novel in vivo breast tumor model. CANCER RES. 2009;69(23):8949-8957.

Fig. 1. p53 inhibits the expansion of mammary stem/progenitor cells. (A) *Trp53-/-* and *Trp53+/-* mammary epithelial cells (MECs) gave rise to significantly higher number of mammospheres than *Trp53+/+* MECs ($p<0.01$). The data shown represent 12 replicates for each genotype. The results were reproduced in a second independent experiment. (B) *Trp53-/-* MECs gave rise to significantly larger mammospheres than *Trp53+/+* MECs upon serial passages ($^{*}p<0.01$, $^{**}p<0.05$). (C) *Trp53-/-* MECs gave a higher outgrowth rate than *Trp53+/+* MECs. (D-F) Both *Trp53+/+* (D, E) and *Trp53-/-* (F, G) outgrowths were histologically normal as shown by whole mount and HE staining. (H) The extent of fat pad filled for each successful outgrowth was recorded and the frequency of mammary stem/progenitor cells was estimated for *Trp53+/+* and *Trp53-/-* using L-Calc software. *Trp53-/-* MECs contained significantly higher frequency of long-term regenerative mammary stem cells than *Trp53+/+* MECs ($p<0.001$). Meanwhile, *Trp53-/-* outgrowths occupied significantly higher percentage of fat pad than the *Trp53+/+* outgrowths ($p<0.01$).



H

Number of Cells	Number of Mice	*Trp53+/+*		*Trp53-/-*	
		Take Rate	Percent Fat Pad Filled	Take Rate	Percent Fat Pad Filled
50,000	3	3(100%)	●●●	3(100%)	●●●
10,000	11	9(81.8%)	●●●◕◕◔◔◔◔	11(100%)	●●●●●●●●●◕◕
5,000	17	6(35.5%)	●●◓◓◔◔	14(82.4%)	●●●●●●●●◕◕◔◔◔◔
2,500	18	4(22.2%)	●◓◓◔	11(61.1%)	●●●●●●●●●●◔
1,000	14	2(14.3%)	◓◔	5(35.7%)	●●●◔◔
100	11	1(9.1%)	◕	2(18.2%)	●◕
Frequency		1 in 8,085		1 in 2,445	
Frequency Range (±1 S.E.)		1 in 6,508 ~ 10,045		1 in 2,033 ~ 2,940	
p value		<0.001			

Fig. 2. p53-mediated apoptosis is compromised in mammary stem/progenitor cells. Single cell suspensions were treated with 0-Gy or 5-Gy γ-irradiation before being plated and the number of secondary (A) and tertiary (B) mammospheres were compared. The mammospheres of different p53 genotypes showed no difference between control (NO-IR) and irradiated (IR) samples ($p>0.05$). The data shown represent 12 replicates for each treatment. The results were reproduced in a second independent experiment.

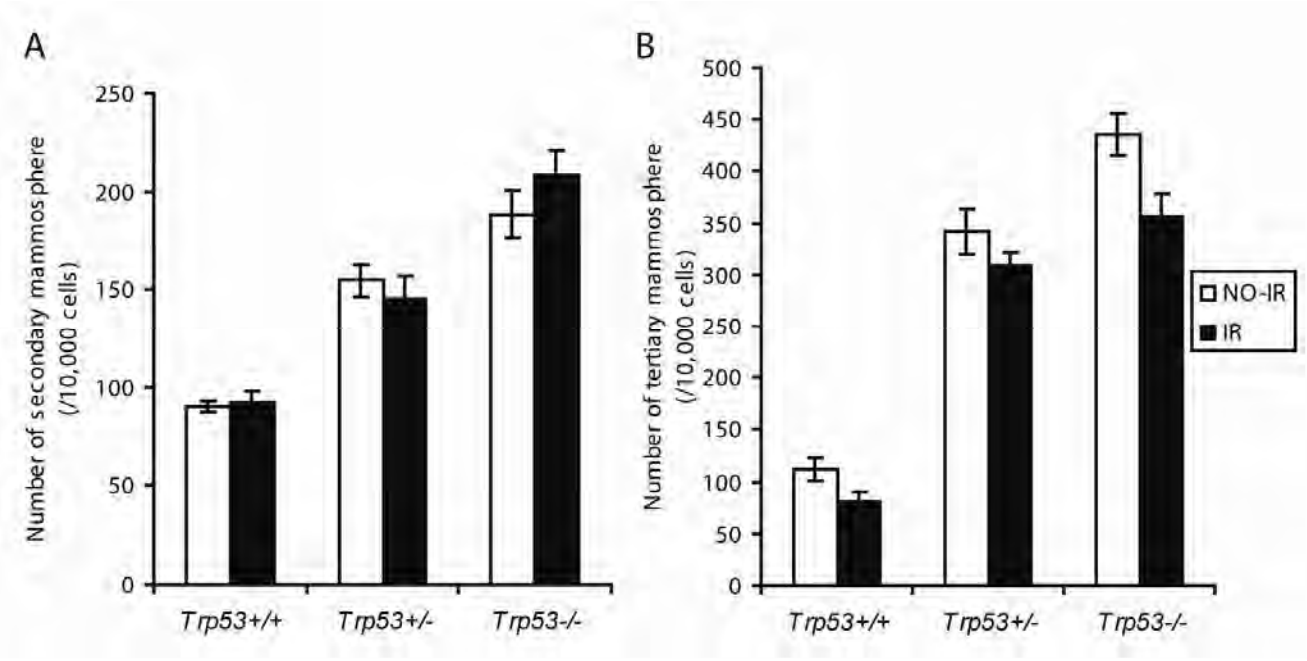


Fig. 3. *Trp53-/-* mammary epithelium contained fewer label-retaining epithelial cells (LRECs). LRECs were found in both luminal and basal compartments and the distribution of LRECs were similar among *Trp53+/+* (A) and *Trp53-/-* (B) mammary glands. Quantitative analysis showed that the *Trp53-/-* glands contained significantly lower number of LRECs than the *Trp53+/+* glands (C) ($p<0.01$).

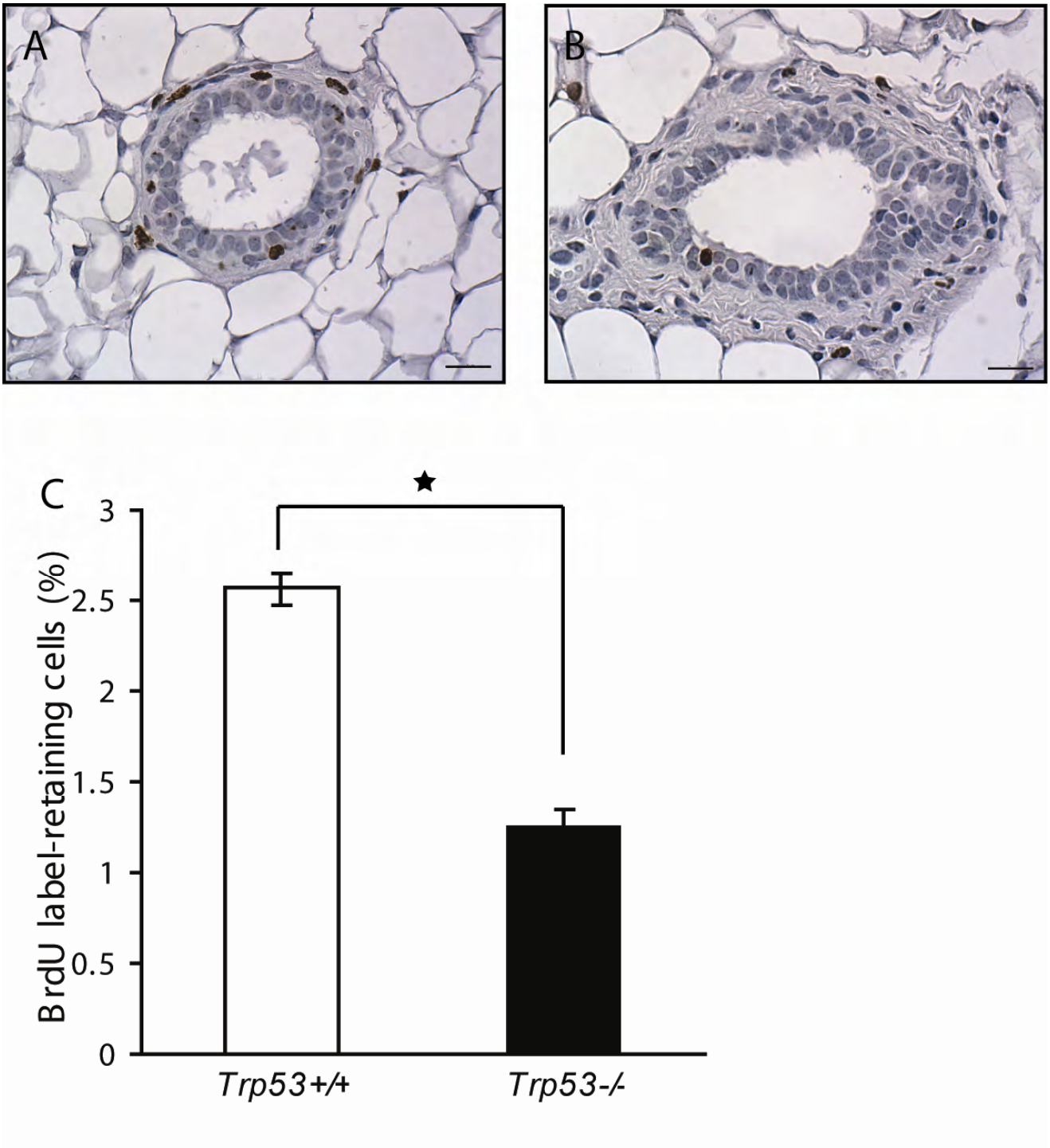


Fig. 4. TM40A cells as an *in vitro* model to test the function of basal level p53. (A) Whole mount of a TM40A outgrowth 20 weeks after transplantation. (B) The let7c-sensor plasmid was introduced into TM40A cells (TM40A-let7^{s}). The TM40A-let7^{s} cells contained 0.8% of DsRed positive (DsR^{+}) progenitor cells. Background levels of fluorescence were determined using control cells. (C) The DsR^{+} cells gave rise to significantly more mammospheres than DsR^{-} cells ($p<0.01$). (D) Most cells in the DsR^{+} mammospheres remained DsRed positive. (E) Western blot showed that phosphorylated p53 (phospho-p53) was reduced in TM40A-let7^{s}-p53KD cells compared to the control cells (TM40A-let7^{s}-ctrl).

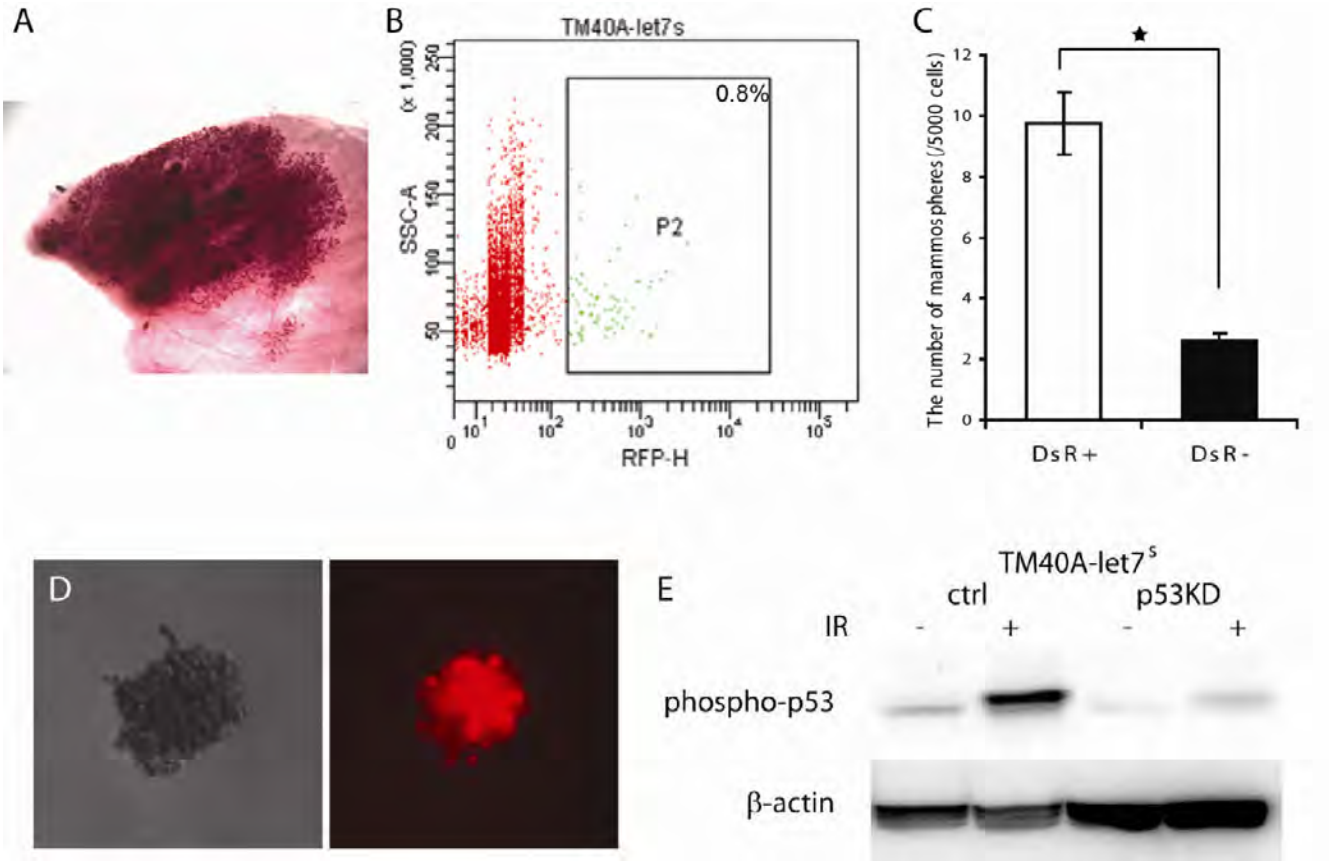
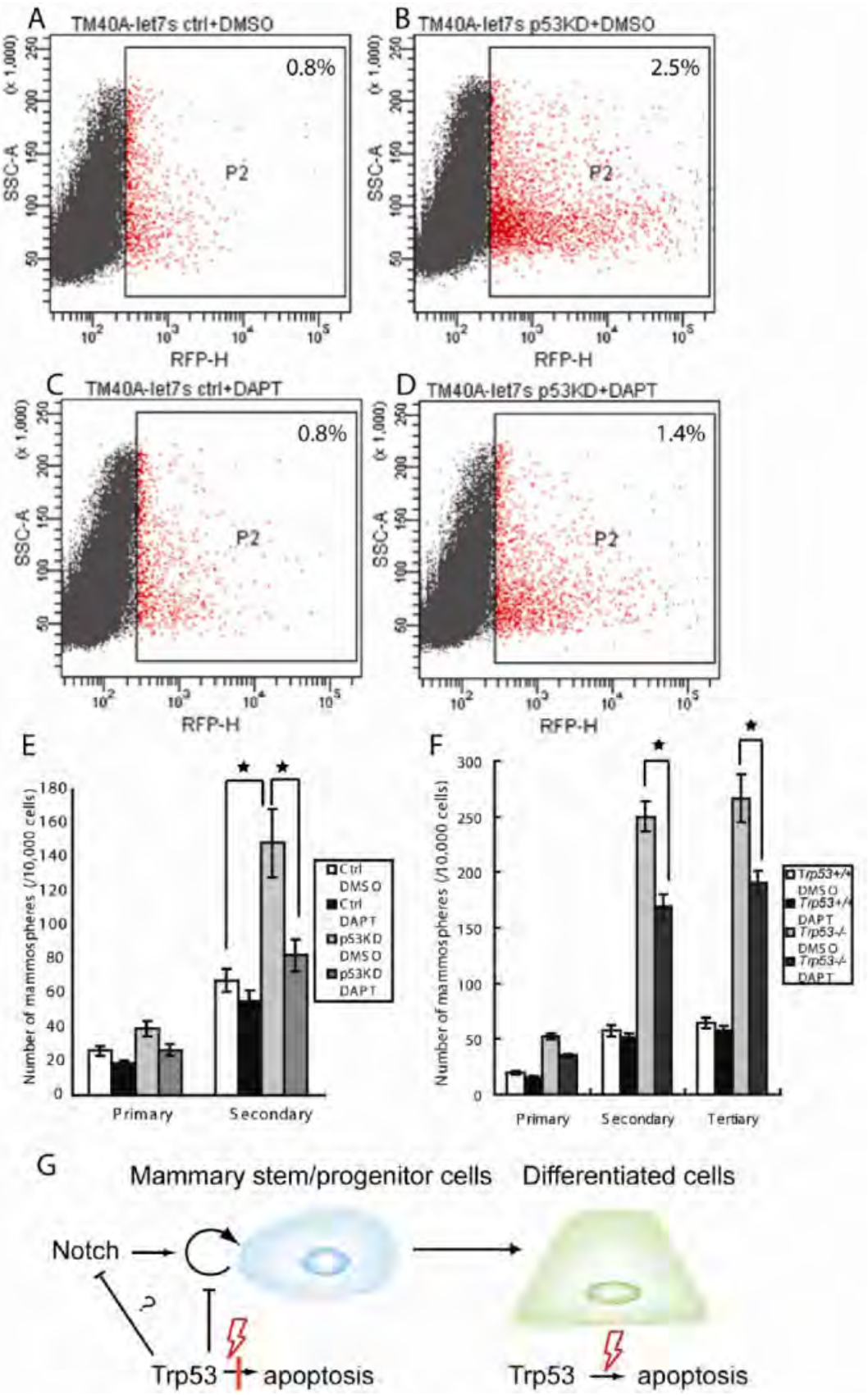


Fig. 5. Inhibition of mammary stem/progenitor cells with γ-secretase inhibitor. (A-D) TM40A-let7^{s}-p53KD cells contained more DsR^{+} progenitor cells compared to the TM40A-let7^{s}-ctrl cells. The expansion of DsR^{+} progenitors in TM40A-let7^{s}-p53KD cells can be inhibited by the treatment of DAPT, while the DsR^{+} cells in TM40A-let7^{s}-ctrl cells were not affected. (E) TM40A-let7^{s}-p53KD cells gave rise to significantly more secondary mammospheres than control cells ($p<0.01$). The number of p53KD mammospheres decreased significantly with the treatment of 5μM DAPT ($p<0.01$), while the number of control mammospheres were not affected ($p>0.05$). (F) Mammospheres were treated with either 5μM DAPT or DMSO control during serial passages. The number of *Trp53-/-* mammospheres decreased significantly after the treatment of DAPT ($p<0.01$). The number of *Trp53*+/+ mammospheres was not changed with DAPT treatment. (G) Model of p53 tumor suppression function in different cell types. p53 restricts the self-renewal of mammary stem/progenitor cells; however the p53-mediated apoptosis response is compromised in these cells. In the differentiated cells, the p53-mediated apoptosis pathway becomes functional. Notch may be inhibited by basal levels of p53 in mammary stem/progenitor cells. Insufficient p53 can result in increased Notch activity which leads to the expansion of mammary stem/progenitor cells.


A
TM40A-let7s ctrl+DMSO
0.8%
P2
SSC-A
RFP-H
B
TM40A-let7s p53KD+DMSO
2.5%
P2
C
TM40A-let7s ctrl+DAPT
0.8%
P2
D
TM40A-let7s p53KD+DAPT
1.4%
P2
E
Number of mammospheres (/10,000 cells)
Ctrl DMSO
Ctrl DAPT
p53KD DMSO
p53KD DAPT
Primary
Secondary
F
Number of mammospheres (/10,000 cells)
Trp53+/+ DMSO
Trp53+/+ DAPT
Trp53-/- DMSO
Trp53-/- DAPT
Primary
Secondary
Tertiary
G
Mammary stem/progenitor cells
Differentiated cells
Notch
?
Trp53
apoptosis
Trp53
apoptosis