Dihydrotestosterone synthesis bypasses testosterone to drive castration-resistant prostate cancer

Kai-Hsiung Chang, Rui Li, Mahboubeh Papari-Zareei, Lori Watumull, Yan Daniel Zhao, Richard J. Auchus, and Nima Sharifi*†

*Division of Hematology and Oncology, †Division of Endocrinology and Metabolism, Department of Internal Medicine, ‡Department of Radiology, and $Department of Clinical Sciences, University of Texas Southwestern Medical Center, Dallas, TX 75390-8852

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In the majority of cases, advanced prostate cancer responds initially to androgen deprivation therapy by depletion of gonadal testosterone. The response is usually transient, and metastatic tumors almost invariably eventually progress as castration-resistant prostate cancer (CRPC). The development of CRPC is dependent upon almost invariably eventually progress as castration-resistant prostate cancer (CRPC). The development of CRPC is dependent upon the androgen, dihydrotestosterone (DHT), from adrenal precursor steroids. Progression to CRPC is accompanied by increased expression of steroid-5α-reductase isoenzyme-1 (SRD5A1) over SRD5A2, which is otherwise the dominant isoenzyme expressed in the prostate. DHT synthesis in CRPC is widely assumed to require 5α-reduction of testosterone as the obligate precursor, and the increased expression of SRD5A1 is thought to reflect its role in converting testosterone to DHT. Here, we show that the dominant route of DHT synthesis in CRPC bypasses testosterone, and instead requires 5α-reduction of androstenedione by SRD5A1. These findings reframe the fundamental metabolic pathway that drives CRPC progression, and shed light on the development of new therapeutic strategies.


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†To whom correspondence should be addressed. E-mail: Nima.Sharifi@UTSouthwestern.edu.

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Androgen deprivation therapy with depletion of gonadal testosterone (T) is the frontline treatment for advanced prostate cancer and is usually initially effective (1). Metastatic disease almost always eventually acquires resistance to gonadal T depletion and is termed “castration-resistant prostate cancer” (CRPC). A critical mechanism in driving CRPC tumor progression is a gain-of-function in the androgen receptor (AR) (2). Multiple clinical studies have shown that intratumoral concentrations of T and 5α-dihydrotestosterone (DHT) sufficient to activate AR-dependent transcription are maintained in CRPC despite suppression of serum T (3–6). The requirement for the intratumoral generation of androgen ligand is exemplified by frequent and often sustained responses to AR antagonists (7, 8), as well as an unprecedented prolongation of survival in chemotherapy-refractory metastatic CRPC conferred by abiraterone acetate, a potent inhibitor of CYP17A1, which is required for the synthesis of adrenal 19-carbon steroid precursors of T and DHT (9).

Although T is a modest AR agonist, DHT is more potent (10) and is the principal androgen bound to AR in the prostate cell nucleus (11). In the setting of CRPC and the absence of gonadal T, dehydroepiandrosterone (DHEA) and its sulfate, the chief adrenal 19-carbon steroid in circulation (12), undergoes conversion to Δ2-androstanediene (AD) in prostate cancer (Fig. 1) by 3β-hydroxysteroid dehydrogenase/isomerase (13–15). Intratumoral synthesis of DHT in CRPC is generally thought to require 17-β-reduction of AD to T, followed by 5α-reduction of T to DHT (2, 6, 16), thereby following the synthesis and processing dictated by gonadal T physiology. This “conventional” pathway (AD→T→DHT) in CRPC has been generally surmised by genetic deficiencies in enzymes required to convert AD to T in
increased T. Silencing SRD5A2 does not reduce SRD5A1 using two independent shRNAs. Notably, blocking when SRD5A1 is knocked down. Synthesis of 5 completely consumed by 48 h, whereas the majority of AD is preserved assessed by HPLC (Fig. 4). In control cells, AD is almost completely metabolized by all six cell-line models alone, as well as the freshly collected human tumors (Fig. S1).

Alternative Pathway Drives CRPC Progression. To test the requirement of the conventional pathway (AD→T→DHT) versus the alternative pathway (AD→5α-dione→DHT) for CRPC growth, we performed subcutaneous xenograft studies with LAPC4 and LNCaP models in surgically orchiectomized mice supplemented with T and AD. A priori, one would expect that the dominance of the alternative pathway in inducing CRPC growth might not be demonstrable given (i) two steps for the transformation of AD to DHT instead of one step for T to DHT, and (ii) modest AR agonist by T but not AD in the absence of further metabolism. Both LAPC4 and LNCaP tumors in mice supplemented with AD reached the predetermined endpoints of tumor volume ≥ 50 mm³ and ≥ 300 mm³ significantly more rapidly than T-supplemented mice (Fig. 3). In general, tumor take in LNCaP was less efficient than with LAPC4, as is consistent with the experience of others (21).

SRD5A1 Is the Dominant Isoenzyme Required for the Alternative Pathway. Several independent studies have shown that expression of SRD5A1 is increased and SRD5A2 is decreased in the transition from hormone-naïve prostate cancer to CRPC (4, 22, 23). However, the role of any increase in SRD5A1 expression is thought to reflect a role in converting T to DHT. To test whether SRD5A1 might catalyze flux from AD→5α-dione in the alternative pathway to DHT to sustain CRPC, both SRD5A1 and SRD5A2 were stably knocked down in LNCaP and LAPC4 using lentiviral shRNAs (Fig. S2), and metabolism from [3H]-AD was assessed by HPLC (Fig. 4). In control cells, AD is almost completely consumed by 48 h, whereas the majority of AD is preserved when SRD5A1 is knocked down. Synthesis of 5α-dione, DHT, and total 5α-reduced steroids is largely blocked by effectively silencing SRD5A1 using two independent shRNAs. Notably, blocking flux from AD→5α-dione by silencing SRD5A1 diverts AD instead to increased T. Silencing SRD5A2 does not reduce flux from AD to 5α-dione, DHT, or other 5α-reduced steroids, suggesting little or no participation of this SRDS5A1 isoenzyme in the alternative pathway. Representative HPLC plots are shown in Fig. S3. Similar experiments done with a SRD5A2 selective concentration of finasteride (24) and a clinically relevant concentration of dutasteride (25) corroborate these findings (Fig. S4).

Blocking SRD5A1 Inhibits AR-Responsive Gene Expression and CRPC Progression. To determine the effect of blocking flux from AD→5α-dione by silencing SRD5A1 expression on AR-dependent transcription, cells with silenced SRD5A1 expression were treated with AD, and prostate-specific antigen (PSA) expression was assessed (Fig. S4). AD-induced PSA expression is muted in the absence of SRD5A1. To determine if the rate of SRD5A1 expression in conducting the alternative pathway is critical to drive CRPC growth, surgery orchiectomized mice supplemented with sustained-release AD pellets were injected subcutaneously with cells expressing an SRD5A1 shRNA or control nonsilencing shRNA (Fig. 5 B and C). Time-to-tumor volume ≥ 50 mm³ was significantly decreased for SRD5A1-silenced LAPC4 cells (P = 0.0364). Although not statistically significant, the trend for the LNCaP model and the volume ≥ 300-mm³ endpoint all consistently suggested disadvantaged growth for cells lacking SRD5A1 expression. SRD5A1 Western blot in tumors collected at the end of study showed that SRD5A1 expression is increased in the knockdown tumors compared with the original cells injected with silenced SRD5A1 expression (Fig. S5). This finding suggests there is selection for higher SRD5A1-expressing cells, which likely underestimates the true requirement for SRD5A1 expression in these xenograft experiments. On the other hand, xenograft growth in 5α-dione-supplemented mice had nearly identical growth between shCTRL and shSRD5A1 groups (Fig. 5D), further demonstrating that the specific role of SRD5A1 in the alternative pathway and CRPC growth is the conversion of AD→5α-dione, and that the differences in tumor growth in Fig. 5 B and C are not the result of other effects of SRD5A1 on growth.

Discussion

DHT in CRPC tumors might derive either from de novo steroidogenesis starting with cholesterol (26) or by metabolism of highly abundant adrenal precursors, which requires only a few enzymes and appears to be the dominant component (27). In contradistinction to widely held assumptions about the major pathway that drives CRPC progression, our findings show that the major metabolic pathway from adrenal precursor steroids to DHT in CRPC circumvents T as an obligate precursor and that the transformation of AD→5α-dione by SRD5A1 is a required step for DHT synthesis and tumor progression. The specific requirement for SRD5A1 in this pathway suggests that SRD5A1 up-regulation, which occurs concurrently with SRD5A2 down-regulation clinically in the transition from hormone-naive prostate cancer to CRPC (4, 22, 23), reflects selection for tumor cells that efficiently synthesize DHT through the alternative pathway. These results are also in line with the initial studies of SRD5A1, which suggest that AD is a better substrate for this isoenzyme than T (28). Notably, this pathway of adrenal steroid metabolism is likely not unique to CRPC (19).

Strikingly, the consistent finding of the dominance of the alternative pathway across all six CRPC cell-line models tested suggests that this is the common pathway shared in CRPC. We took the further step to biopsy tumors from two patients, which yielded results that are exactly the same as the cell-line models, as well as the stromal cocultures. Together, these results confirm that the findings in the models tested are not merely attributable to an artifact in cell-line models and, furthermore, are of clinical importance to our knowledge that the metabolic pathways in metastatic CRPC are unprecedented. It is important to note that studies on “banked” tissue, which is enzymatically dead, give a snapshot picture of androgen concentrations at one point in time (3, 4). Our studies and approach require enzyme activity in freshly obtained tumors from patients to define the interconversion of these steroids and their origins.
The current findings must be reconciled with several observations that were interpreted to support the conventional pathway requiring T. First, although untreated prostate cancer and benign prostate have lower concentrations of T than DHT (T:DHT ratio = ~1:10), indicating rapid and irreversible flux from T→DHT, clinical studies of CRPC indicate that this ratio is reversed and that concentrations of T are higher than DHT. These studies are generally interpreted to suggest that any DHT must arise from T. In contrast, an alternative explanation for the increase in precursor (T) to product (DHT) ratio is that flux to DHT may not occur readily through T but rather through the alternative route. In an analogous scenario, pharmacologically blocking flux from T→DHT in the prostate of eugonadal men yields similar increases in the T:DHT ratio as in CRPC (3, 4, 29). We would suggest that in CRPC a modicum of T synthesis is sufficient to increase the T:DHT ratio because T is not readily converted to DHT. With respect to the relative concentrations and contributions of T and DHT as AR agonists, it is important to note that intratumoral concentrations of androgens in clinical studies disproportionately reflect androgens found in the tumor interstitial space and cellular cytoplasm. On the other hand, intranuclear concentrations of androgens more accurately reflect the active androgen bound to AR (11). Nuclear DHT concentrations have not been determined in clinical CRPC tissue, and we would suggest this compartment is likely enriched with DHT beyond those observed in the sum of all tumor compartments (3, 4).

Second, clinical trials of the dual SRD5A inhibitor, dutasteride, that only showed modest clinical activity against CRPC (30) might be interpreted to signify a limited importance for DHT. However, our findings (Fig. S4) suggest that a pitfall of pharmacologically blocking SRD5A1 and the conversion of AD to 5α-dione is the diversion of AD to T, generating higher concentrations of T, which has modest AR agonist activity, and may thereby partially compensate for blocking DHT synthesis. This explanation is supported...
bars represent the SD.

dependent on SRD5A1 but not SRD5A2 expression. Blocking AD
SRD5A2 silenced cells, but AD is largely preserved and not metabolized in SRD5A1 silenced cells. Synthesis of 5 
AD in triplicate, with HPLC quantitation of the indicated steroids at the designated time points. In both models, AD is depleted over time in control and 
nonsilencing (shCTRL), SRD5A1 silencing (shSRD5A1 #1 and #4) and SRD5A2 silencing (shSRD5A2 #516 and #816) lentiviral constructs were treated with[3H]-

Fig. 3. The alternative pathway to DHT synthesis drives CRPC progression. CRPC growth in the LAPC4 (Upper) and LNCaP (Lower) CRPC models have more robust growth in orchiectomized mice supplemented with AD versus T (0.25 mg sustained-release steroid pellets). Control mice underwent orchiectomy and no steroid supplementation. Time from injection of tumor cells to tumor volume \( \geq 50 \text{ mm}^3 \) (Left) and tumor volume \( \geq 300 \text{ mm}^3 \) (Right) is statistically significantly different for both models and both endpoints using a log rank test and a pairwise comparison of AD versus T cohorts.

by the higher concentrations of T that occur with SRD5A1 knockdown, and the lack of complete inhibition of AR-dependent transcription and CRPC growth (Fig. 5). These findings suggest that the best points of pharmacologic intervention to treat CRPC should not shunt synthesis from one AR agonist (DHT) to another (T).

Our observation that DHT is synthesized through an alternative pathway involving conversion of AD to 5α-dione by SRD5A1 has broad implications for the development of new therapeutic agents and for determining mechanisms of resistance to hormonal therapies for CRPC. These data suggest that blocking the conversion

Fig. 4. SRD5A1 is required for the conversion of AD to 5α-dione in the alternative pathway to DHT synthesis. (A) LAPC4 and (B) LNCaP cells stably expressing nonsilencing (shCTRL), SRD5A1 silencing (shSRD5A1 #1 and #4) and SRD5A2 silencing (shSRD5A2 #516 and #816) lentiviral constructs were treated with [3H]-AD in triplicate, with HPLC quantitation of the indicated steroids at the designated time points. In both models, AD is depleted over time in control and SRD5A2 silenced cells, but AD is largely preserved and not metabolized in SRD5A1 silenced cells. Synthesis of 5α-dione, DHT and total 5α-reduced steroids are dependent on SRD5A1 but not SRD5A2 expression. Blocking AD→5α-dione by silencing SRD5A1 hastens conversion of AD→T, resulting in elevated T. Error bars represent the SD.
of AD to T will not significantly inhibit DHT synthesis in CRPC. Furthermore, our findings suggest that T may not be the best marker for monitoring the intratumoral response or resistance to upstream inhibitors of adrenal steroid synthesis, such as abiraterone acetate (31). Future studies of intratumoral androgens should include previously unappreciated DHT intermediates.

Methods

Cells and Culture Conditions. The 22Rv1, LNCaP, and DU145 prostate cancer cell lines and HS-27A bone marrow stromal cells were purchased from ATCC and maintained in RPMI 1640 with 10% FBS. VCaP cells were purchased from ATCC and maintained in DMEM with 10% FBS. The LAPC4 prostate cancer cell line was generously provided by Charles Sawyers (Memorial Sloan Kettering Cancer Center, New York, NY) and was grown in Iscove’s modified Dulbecco’s

Fig. 5. SRD5A1 is required for PSA expression and CRPC tumor progression in vivo. (A) Silencing SRD5A1 expression blunts PSA expression in response to AD, which is a substrate for SRD5A1, but not R1881, which does not require metabolism to bind AR. PSA expression is normalized to RPLP0 and vehicle (EtOH) control. Error bars represent the SD of experiments performed in triplicate. (B) Silencing SRD5A1 expression inhibits CRPC growth in orchiectomized mice supplemented with AD, as assessed by time for LNCaP and LAPC4 tumors to reach 50 mm³ and (C) 300 mm³. Only LAPC4 tumors reaching the 50-mm³ endpoint was statistically significantly different, although the trend for all models and time points had a disadvantage for the shSRD5A1 group. (D) Bypassing the requirement for SRD5A1 by supplementing orchiectomized mice with 5α-dione leads to nearly superimposable growth for control and shSRD5A1 LAPC4 cells. Control and shSRD5A1 groups for all xenograft studies were compared using a log rank test.
Steroid Metabolism. Cells were seeded in 12-well dishes at 300,000 to 400,000 cells per well 24 h before the experiment in serum-free, phenol red-free medium. In coculture experiments, tumor and stromal cells were plated at a 1:1 ratio. [3H]-labeled steroids (100 nM, 300,000-600,000 cpm) were obtained from PerkinElmer, added in ethanol, and then cells were incubated at 37 °C for up to 48 h. Cells were concomitantly treated with finasteride (Sigma-Aldrich) and dutasteride (GlaxoSmithKline), indicated where. Aliquots of medium (0.25–0.5 mL) were treated with 1,000 units of β-glucuronidase (Helix Pomatia; Sigma-Aldrich) at 65 °C for 4 h to deconjugate glucuronidated steroids, extracted with 1 mL 1:1 ethyl acetate/isooctane, and concentrated under nitrogen. For HPLC analysis, the dried samples were dissolved in methanol and injected on a Breeze 1525 system equipped with model 717 plus autoinjector (Waters Corp.) and a Kinex 100 × 2.1-mm, 2.6 μm C18 reverse-phase column (Phenomenex) and methanol/water gradients at 30 °C. The column effluent was analyzed using a j-1-RAM model 3-in-line radioactivity detector (INUS Systems, Inc.) using Liquiscint scintillation mixture (National Diagnostics). Alternatively, dried samples were applied to plastic-backed silica detector (IN/US Systems, Inc.) using Liquiscint scintillation mixture (National Diagnostics). Quantitative PCR (qPCR) analysis was performed in triplicate with the primer set for SRD5A1 (Forward: 5′-CTCTTGGAATGCTTCATGACTTG-3′; Reverse: 5′-TAAGGCAAAACAGTGCTAGT-3′), SRD5A2 (Forward: 5′-CTCCTCAAAGAGGGGCGAAC-3′; Reverse: 5′-GACAACTGATTCCGAAAATA-3′), PSA (Forward: 5′-GATGGGATGGGAGTGAGTAAG-3′; Reverse: 5′-CATCAAACTTGGGTTGTGCA-3′), and the housekeeping gene encoding large ribosomal protein P0 (RPLP0) (Forward: 5′-CACATTCCCCCGGATATGA-3′; Reverse: 5′-TAAGGCAAAGCAATGCCA-3′). The mRNA expression level was then normalized to the sample values to RPLP0 and to nonsilencing control cells (for knockdown) and analyzed by HPLC as described above. For patient #2, there was also sufficient tissue for treatment with [3H]-T, done under the same conditions as the [3H]-AD treatment described above.

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References

**Supporting Information**

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**SI Materials and Methods**

**Lentiviral Knockdown.** To knock down endogenous SRD5A1, four different miR30-based human SRD5A1 target antisense sequences (1: 5′-TTTTGTATCCAGTATCCTCGG-3′; #2: 5′-ATATTCAACCTCATTTCAGCG-3′; #3: 5′-TAAAGTCACTGCTCATACAC-3′; #4: 5′-ATACTCTCAATTTCCGGAGG-3′) were derived from siDESIGN-Center at http://www.dharmacon.com/designcenter/designcenterpage.aspx. The miR30-styled shRNA was generated by adding a miR-30 loop and appropriate flanking sequence of miR-30, as described previously (1) and synthesized as a single-stranded DNA template. PCR amplification was performed using Advantage-GC PCR kit (Clontech) with 5′-miR30PCRXho1F (5′-CAGAAGGCTCGAGAAGGTATATTGCTGTTGACAGTGAGCG-3′) and 3′-miR30PCR-BamH1F (5′-CTAAAGTAGCCCCTTGGATCCGGCAGGGTAGGCA-3′). The final PCR products were purified, cloned between the Xho1 and BamH1 sites of pGIPZ empty vector (Open Biosystems), and confirmed by sequencing. The pGIPZ vector with nonsilencing control shRNA and vectors containing shRNA against SRD5A2 were purchased from Open Biosystems.

Fifteen micrograms of pGIPZ vector together with 7.5 μg of each packaging vector (pMD2.G and psPAX2) were co-transfected into 293T cells. Supernatant containing lentivirus particles was harvested 48 h after transfection, passed through a 0.45-μm membrane filter, and directly used to infect prostate cancer cells in the presence of 6 μg/mL polybrene. After 24 h, the infected cells were maintained in the medium with 2 μg/mL puromycin for 2 wk before knockdown assessment.

**Mouse Xenograft Studies.** Male NOD/SCID mice (6- to 8-wk-old) were obtained from the University of Texas Southwestern Animal Resources Center, and xenograft studies were performed under an Institutional Animal Care and Use Committee-approved protocol. To compare xenograft growth with AD vs. T, mice underwent surgical orchietomy and subcutaneous implantation with 90-d sustained-release AD or T pellets (0.25 mg; Innovative Research of America), or no pellet (negative control). Two days later, mice underwent subcutaneous injection with 1 × 10⁷ cells (n = 10 mice per group for LAPC4; n = 8 mice per group for LNCaP), along with matrigel. Experiments for comparisons of shCTRL vs. shSRD5A1 cells in AD treated mice were similarly performed using orchietomized mice and 0.25 mg AD pellets, except n = 9 mice in each group for LAPC4 and to compensate for the generally poorer tumor take in LNCaP, 20 mice were all injected with shCTRL in the right flank and shSRD5A1 in the left flank. The comparison of LAPC4 shCTRL vs. shSRD5A1 mice used n = 12 mice per group.

Tumor dimensions were measured two to three times per week, and volume was calculated as length × width × height × 0.52. Time to the predetermined endpoints of tumor volume ≥ 50 mm³ and 300 mm³ were calculated as a percentage using a denominator of mice that were alive along with mice that died or were killed because of tumor growth. This analysis excludes mice that died from mortality unrelated to tumor growth (generally ≤ 10%). The time to tumor volume ≥ 50 mm³ and ≥ 300 mm³ were compared between the AD and T groups (Fig. 3), AD treated shCTRL vs. shSRD5A1 (Fig. 5 B and C), and 5α-dione treated shCTRL vs. SRD5A1 (Fig. 5D), using a log rank test. A P value of less than 0.05 was considered significant.

The alternative pathway of Δ4-androstenedione (AD) metabolism is dominant in castration-resistant prostate cancer (CRPC) cocultures with bone marrow stromal cells. LAPC4 and LNCaP were cocultured with HS-27A human bone marrow stromal cells, and flux from [3H]-AD and [3H]-testosterone (T) was analyzed by HPLC. (A) Flux from AD→5α-dione occurs more robustly than from AD→T. (B) The 5α-reduction of AD→5α-dione is preferred over T→DHT. Error bars represent the SD.

Fig. S1.
Fig. S2. Steroid 5α-reductase isoenzyme-1 (SRD5A1) and SRD5A2 expression is effectively silenced by stable expression of lentiviral shRNA constructs. LNCaP and LAPC4 cells were infected with control (shCTRL) and candidate lentiviral constructs (shSRD5A1 and shSRD5A2) to silence SRD5A isoenzyme expression. Expression was assessed by qPCR in triplicate and Western blot. Expression of SRD5A isoenzyme by qPCR is expressed relative to shCTRL and normalized to RPLP0. Cells exhibiting effective knockdown (shSRD5A1 #1, shSRD5A1 #4, shSRD5A2 #516 and shSRD5A2 #816) were selected for other experiments. Error bars represent the SD.
Expression of SRD5A1 but not SRD5A2 is required for generation of 5α-dione and DHT. Representative HPLC tracings of steroid metabolites from [3H]-AD treatment in (A) LAPC4 and (B) LNCaP cells expressing nonsilencing control (shCTRL), SRD5A1 knockdown (shSRD5A1 #4), and SRD5A2 knockdown (shSRD5A2 #516) lentiviral constructs.

Fig. S3. Expression of SRD5A1 but not SRD5A2 is required for generation of 5α-dione and DHT. Representative HPLC tracings of steroid metabolites from [3H]-AD treatment in (A) LAPC4 and (B) LNCaP cells expressing nonsilencing control (shCTRL), SRD5A1 knockdown (shSRD5A1 #4), and SRD5A2 knockdown (shSRD5A2 #516) lentiviral constructs.
The effects of finasteride and dutasteride on the alternative pathway. (A) Finasteride does not affect the conversion of AD→5α-dione in LAPC4 and LNCaP cells. (B) At a clinically relevant concentration, dutasteride completely blocks conversion of AD→5α-dione, as well as DHT synthesis, resulting in diversion of AD→T. Error bars represent the SD.

Fig. S4.
Fig. S5. SRD5A1 knockdown is partially reversed in tumors that develop in orchiectomized mice supplemented with AD. (A) Western blots of SRD5A1 from three shCTRL and three shSRD5A1 LAPC4 tumors. (B) SRD5A1 protein quantitation in three shSRD5A1 tumors relative to the mean SRD5A1 in the three shCTRL tumors. Protein is graphed as the fold-increase in expression compared with the original shSRD5A1 #4 cell (Fig. S2) before injection and in vivo growth selection.