Enhanced Response to Mouse Thyroid-Stimulating Hormone (TSH) Receptor Immunization in TSH Receptor-Knockout Mice

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Graves-like hyperthyroidism is induced in BALB/c mice by immunization with adenovirus expressing the human TSH receptor (TSHR) A-subunit (amino acids 1–289). However, because of nonidentity between the human and mouse TSHR (−87% amino acid homology), we compared the responses of mice immunized with adenoviruses expressing either the mouse or the human TSHR A-subunit. Wild-type (wt) BALB/c mice immunized with the mouse A-subunit developed neither TSHR antibodies (measured by flow cytometry) nor thyroid lymphocytic infiltration. However, wt C57BL/6 mice developed sparse intrathyroidal lymphocyte infiltration without antibody production. Depletion of naturally occurring regulatory CD4+CD25+ T cells had little effect. These results indicate the inability to break tolerance to the mouse TSHR in wt mice. In contrast, TSHR knockout (KO) BALB/c mice generated mouse TSHR antibodies in response to mouse A-subunit immunization and augmented human TSHR antibody response to human A-subunit immunization. Thyroid-stimulating antibody titers measured in a functional bioassay were comparable in human A-subunit immunized wt mice and in TSHR KO mice immunized with either the mouse or human A-subunit. In conclusion, immune response to the mouse TSHR is readily induced in TSHR KO but not in wt mice. Only in the former does immunization with adenovirus expressing the mouse A-subunit generate antibodies capable of activating the mouse TSHR. TSHR KO mice are, therefore, of value for future studies dissecting the autoimmune response to the mouse TSHR. (Endocrinology 151: 4047–4054, 2010)

Graves’ disease is a common organ-specific autoimmune disease that targets the thyroid gland. It is mediated by an abnormal humoral immune response against the TSH receptor (TSHR), a thyroid-specific antigen. Thus, agonistic TSHR antibodies (thyroid-stimulating antibodies; TSAb) cause overproduction of thyroid hormones and diffuse enlargement of the thyroid gland (reviewed in Ref. 1). We previously generated a murine model of experimental Graves’ disease by intramuscular injection of recombinant adenovirus encoding the full-length human TSHR (764 amino acids) (Ad-human TSHR) (2) or the TSHR A-subunit (amino acids 1–289) (Ad-human TSHR289; hereafter Ad-human TSHR A-subunit) (3). This approach is highly efficient for inducing TSAb and Graves-like hyperthyroidism in a susceptible mouse strain (BALB/c). All other Graves’ mouse models so far reported also involved immunization with the human TSHR cDNA (reviewed in Ref. 4) with one exception which used the mouse TSHR cDNA (5). To produce hyperthyroidism, TSAb induced by immunization with the human TSHR must cross-react with and stimulate the endogenous mouse TSHR. However, heterologous antigens are usually more antigenic than homologous self-antigens. Indeed, homology between the human and mouse TSHRs

Abbreviations: AIRE, Autoimmune regulator; CHO, Chinese hamster ovary; IRBP, interphotoreceptor retinoid-binding protein; KO, knockout; T4, thyroxine; TSA, tissue-specific self-antigen; TSAb, thyroid-stimulating antibodies; TSH, TSH receptor; wt, wild type.
is approximately 87% at amino acid levels (6, 7). Furthermore, different pathogenic mechanisms can be elicited by antigens from different species, as observed in a murine model of experimental autoimmune encephalitis (8). Therefore, the present study was performed to compare the immunogenicity of the human and mouse TSHR antigens in our murine model using wild-type (wt) and TSHR knockout (KO) mice.

Materials and Methods

Mice
Female wt BALB/c and C57BL/6 (B6) mice (6 wk old) were purchased from Charles River Japan Laboratory Inc. (Tokyo, Japan). B6/129 mice genetically deficient for the TSHR (9) were obtained from The Jackson Laboratory (Bar Harbor, ME) and were backcrossed to wt BALB/c mice for six successive generations. Genotyping was done using tail DNA as previously described (9). Expression of H-2d and not H-2k was confirmed by flow cytometry using fluorescein isothiocyanate- or phycoerythrin-conjugated anti-major histocompatibility complex class II antibodies (clone 7-16.17 and M5/114.15.2; from BD PharMingen, San Jose, CA and eBioscience, San Diego, CA, respectively). Flow cytometry was performed using FACSCanto II (BD Biosciences, San Diego, CA). All the mice were kept in a specific pathogen-free facility. Animal care and all experimental procedures were performed in accordance with the Guideline for Animal Experimentation of Nagasaki University with approval of the Institutional Animal Care and Use Committee.

Recombinant adenoviruses and immunization protocol
Nonreplicative recombinant human adenovirus expressing the human TSHR A-subunit (Ad-human TSHR A-subunit) was previously constructed (3). The same adenovirus vector expressing the mouse TSHR A-subunit (Ad-mouse TSHR A-subunit) was constructed as described previously for the human A-subunit (3). Briefly, the gene encoding the mouse TSHR A-subunit (amino acids 1–289), amplified by PCR from pcDNA5/FRT-mouse TSHR (10) as a template, was ligated into the adenovirus shuttle vector pHMCMV6. After verification of the nucleotide sequence, the DNA fragment coding CMV promoter, the TSHR sequence, the DNA fragment coding CMV promoter, the TSHR sequence, and the poly A signal was inserted into pAdHM14, yielding pAd-HM14-TSHR A-subunit. Adenovirus was produced by transfecting Pac I-digested pAd-HM14-TSHR A-subunit into 293 human embryonal kidney cells. Amplification, purification, and determination of the viral particle concentration were as described previously (2).

Mice were injected intramuscularly in the quadriceps with 100 μl PBS containing 10^10 or 10^8 particles of adenovirus on two occasions at 3-wk intervals. Groups of mice were also treated by ip injection of 250 μg/mouse anti-CD25 monoclonal antibody (PC61) (11) 4 d before the first immunization. Blood, spleens, and thyroid tissues were obtained 2 wk after the final immunization.

Detection of TSHR A-subunits by immunoblotting
Expression of TSHR was determined by immunoblotting with 40 μg of total cell lysates prepared from COS-7 cells either mock-infected or infected with Ad-human TSHR A-subunit or Ad-mouse TSHR A-subunit (multiplicity of infection of 10,000 particles per cell). The signal was developed with our monoclonal human TSHR antibody (3H9) (12) and horse radish peroxidase ABC method (Vectastatin ABC kit, Vector Laboratories, Burlingame, CA).

T4 and TSHR antibody measurements
Serum-free T4 concentrations were measured with a RIA kit (DPC free T4 kit; Diagnostic Products, Los Angeles, CA). The normal range was defined as the mean ± 3 SD of control untreated mice.

TSHR antibodies in mouse sera were determined using two different methods. The first was a TSAb functional bioassay that measures TSAb and was performed with Chinese hamster ovary (CHO) cells stably expressing similar levels of either the human or the mouse TSHR (CHO-human TSHR and CHO-mouse TSHR) (10). Briefly, cells (3 × 10^5 cells per well in a 96-well culture plate) were incubated in 100 μl hypotonic Hanks’ balanced salt solution containing 0.5 mM isobutyl-methylxanthine, 20 mM HEPES, 0.25% BSA, and 5 μl sera (1:20 dilution) or 10^{-7} M bovine (b) TSH (Sigma-Aldrich, St. Louis, MO) as positive control for 2 h at 37 C.

The second assay for TSHR antibodies to the native TSHR (irrespective of their function) used flow cytometry with CHO-human TSHR and CHO-mouse TSHR cells. Briefly, the cells were incubated for 60 min with PBS containing mouse sera (1:100 dilution) followed by fluorescein isothiocyanate-con-

FIG. 1. Western blot analysis of TSHR expression in COS cell infected with Ad-human TSHR A-subunit or Ad-mouse TSHR A-subunit (A), and amino acid sequence alignment of the human and mouse TSHR A-subunits (amino acids 1–289) (B). A, The total cell lysates from control COS cells and those infected with Ad-human TSHR A-subunit or Ad-mouse TSHR A-subunit were subjected to Western blotting as described in the Materials and Methods. B, Amino acid residues assigned for antibody binding sites are boxed (Refs. 27 and 28). N-linked glycosylation sites are underlined.
jugated antimouse IgG antibody (F2772, Sigma-Aldrich) for 60 min. Cells were analyzed using FACSCanto II as previously described (11).

Thyroid histology
Thyroid histology was examined with hematoxylin and eosin (H&E) staining of formalin-fixed tissue sections.

Statistical analysis
Data on the titers of antibodies were analyzed by *t* test. A *P* value <0.05 was considered statistically significant.

Results

Adenovirus expression of the mouse TSHR A-subunit protein *in vitro*
To confirm mouse A-subunit expression by Ad-*mouse* TSHR A-subunit, COS-7 cells were infected with Ad-

![FIG. 2.](https://academic.oup.com/endo/article-abstract/151/8/4047/2456986)

**FIG. 2.** Free T4 concentrations and TSHR antibody titers determined by flow cytometry in sera from control and immunized wt BALB/c and B6 mice. Mice were left untreated (cont) or immunized twice with Ad-*human* or mouse A-subunits and bled 2 wk after second immunization. Some mice were depleted of Treg using anti-CD25 (PC61). Serum free T4 was measured by RIA (A, D, and G) and TSHR antibodies by flow cytometry using CHO-human TSHR (B, E, and H) and CHO-mouse TSHR cells (C, F, and I) as shown in the Materials and Methods. Data for individual mice are shown as ng/dl for free T4 and as % control of the mean fluorescence index (MFI) for TSHR antibodies.

Immunization of BALB/c and B6 mice with adenoviruses expressing the mouse or human TSHR A-subunit
Wt BALB/c and B6 mice, which are susceptible and resistant, respectively to induced hyperthyroidism (2), were immunized twice with Ad-*mouse* TSHR A-subunit or Ad-*human* TSHR A-subunit. Serum T4 and anti-TSHR antibody levels were measured 2 wk after the second immunization. Although increased T4 levels were observed in seven of 10 BALB/c mice immunized with 10^10^ particles of the *human* A-subunit (Fig. 2A), serum T4 levels were unchanged relative to controls in BALB/c or B6 mice immunized with the *mouse* A-subunit (10^10^ or even 10^11^ particles) (Fig. 2, D and G). Likewise, TSHR antibodies determined by flow cytometry using CHO-*human* TSHR cells were positive in most mice immunized with 10^10^ particles of the *human* A-subunit (Fig. 2B), but those determined with CHO-*mouse* TSHR were negative in both BALB/c and B6 strains immunized with 10^11^ particles of the mouse A-subunit (Fig. 2, F and I). Naturally occurring regulatory CD4+CD25+ T cells (Treg) are a T cell subset that negatively regulates the immune response (11). Treg depletion with anti-CD25 (PC61) had no detectable effect on T4 or antibody levels (Fig. 2, D–I).

We also evaluated cross-reactivity for the mouse TSHR of antibodies induced by immunization with the human A-subunit. Unlike their recognition of the human TSHR expressed on the surface of CHO cells (Fig. 2B), these antibodies exhibited minimal binding to CHO-*mouse* TSHR cells (Fig. 2C). However, these antibodies indeed induced hyperthyroidism *in vivo* as mentioned above (Fig. 2A) and showed comparable TSAb activities on
CHO-mouse TSHR and CHO-human TSHR cells (Fig. 3, A and B).

Histological examination revealed that the thyroid glands from human A-subunit immunized wt BALB/c mice showed thyroid hyperplasia typical of Graves’ disease, but without lymphocyte infiltration (data not shown), as reported previously (2). However, a small proportion (20–33%) of the thyroids from wt B6 mice immunized with the mouse A-subunit had sparse intrathyroidal lymphocyte infiltration (Fig. 4 and Table 1). As for TSHR antibody induction, Treg depletion had little effect on thyroiditis.

There are two major findings in the foregoing experiments. First, it is extremely difficult to break tolerance and induce antibodies to the mouse TSHR on immunizing wt mice with the mouse A-subunit (even with Treg depletion). Second, although antibodies generated by human A-subunit immunization in BALB/c mice are functional in that they induce hyperthyroidism, cross-reactivity with the mouse TSHR is poor, at least as detected by flow cytometry.

Immunization of TSHR KO BALB/c mice with adenovirus expressing the mouse or human A-subunit

In principle, TSHR KO mice should not be tolerant to the mouse TSHR and, therefore, a stronger response could be anticipated to immunization with the mouse A-subunit. However, TSHR KO mice were originally on a B6/129 background that is resistant to induction of hyperthyroidism when immunized with the human A-subunit (2).

Therefore, we back-crossed these mice for six generations onto a BALB/c background.

Indeed, unlike wt BALB/c mice (Fig. 2F), TSHR KO BALB/c mice immunized with the mouse A-subunit developed high titers of TSHR antibodies as detected by flow cytometry with CHO-mouse TSHR cells (Fig. 5A). In addition, TSHR KO mice responded vigorously to immunization with the human A-subunit as measured using CHO-human TSHR cells (Fig. 5D). The following comparisons provide insight into immune responses to the mouse vs. human TSHR:

1) The levels of antibodies induced using the human A-subunit (and measured using the human TSHR) were higher in TSHR KO mice than in wt mice (Fig. 5D vs. Fig. 2B) ($P < 0.01$).

2) Antibodies induced in TSHR KO mice to the mouse A-subunit bound well to the mouse TSHR but cross-reacted poorly with the human TSHR (Fig. 5A vs. 5B) ($P < 0.05$).

3) In contrast, antibodies induced to the human A-subunit, which bound to the human TSHR, cross-reacted well with the mouse TSHR (Fig. 5D vs. 5C).

In terms of biological activity in vivo, induced TSHR antibodies will have no effect on thyroid function in TSHR KO mice because the thyroids in these mice lack the TSHR. However, functional TSHR antibodies can be assayed in vitro using CHO-mouse or human TSHR cells. Regardless of which cell type was used, TSAb was detectable in sera from some of the mice whether immunized with the mouse or human A-subunits (Fig. 6). As with flow cytometry, TSAb activity was more readily detectable in the sera of mice immunized with the mouse A-subunits than in CHO-human TSHR cells (Fig. 6, A and B), but a difference was not statistically significant, presumably because of variability of TSAb values. Finally, the thyroid glands from TSHR KO mice showed no histological change upon immunization (data not shown).

Discussion

Despite our previous report showing efficient induction of TSAb and Graves-like hyperthyroidism in BALB/c mice by immunization with Ad-human TSHR A-subunit (3), we were unable to elicit TSHR antibodies by immunizing the same mouse strain with the mouse homolog (Ad-mouse

FIG. 3. TSAb activities in sera from control and immunized wt BALB/c mice measured by a bioassay using CHO-mouse (A) or human (B) TSHR cells. Sera used in Fig. 2A were subjected to a TSAb assay (described in Materials and Methods). TSAb values (means of duplicated assays, % control and pmol/well) are shown for individual mice. cAMP produced by $10^{-7}$ M bTSH was also shown.
TSHR A-subunit). B6 mice, which are resistant to developing hyperthyroidism after immunization with the human A-subunit, were also tolerant of the mouse A-subunit in terms of antibody production, and only a minority of animals developed sparse intrathyroidal lymphocyte infiltration. Depletion of Treg had no effect on TSHR antibody generation or thyroiditis in either mouse strain. These results show that it is extremely difficult to break tolerance (particularly in terms of antibody) against the mouse TSHR in mice.

Central tolerance is a mechanism for preventing harmful immune responses to self-antigens. Ectopic expression of a large array of tissue-specific self-antigens (TSAs) in thymic medullary epithelial cells (mTECs) is found to be critical for this type of tolerance (14, 15). Such promiscuous expression of TSAs in thymic medulla induces effective negative selection (e.g. clonal deletion) of TSA-specific self-reactive T cells. Thymic expression of some but not all self-antigens is controlled by the transcription factor autoimmune regulator (AIRE). For example, AIRE KO mice lack thymic expression of insulin and develop type 1 diabetes in their early life (16, 17). Mutations in AIRE in mice cause an autoimmune disorder that affects a spectrum of organs, and those in humans result in autoimmune disease autoimmunity polyendocrine syndrome 1 (APS-1) (14, 15). However, thymic expression of the mouse TSHR and the time course and magnitude of antibody responses to Ad-human TSHR A-subunit immunization have recently been shown to be only moderately influenced by the absence of AIRE (18).

TSHR KO mice lack thymic expression of the TSHR and are unable to develop central tolerance to the TSHR. Importantly, TSHR antibodies were induced in TSHR KO BALB/c mice by immunization with the mouse A-subunit, consistent with the fact that the mouse TSHR is no longer an autoantigen. Although these mice cannot develop hyperthyroidism because they lack TSHR expression in the thyroid, their sera contain strong TSAb activities, the levels being comparative, or even superior, to those in wt BALB/c mice immunized with Ad-human TSHR A-subunit, indicating that TSHR KO BALB/c mice can generate a potent immune response to the mouse TSHR. Thus thymic expression of this molecule likely sets the threshold of the immune response to the TSHR.

Incidentally, TSHR KO mice were previously tested for their immune response to the full-length human TSHR (19). However, immunization was performed by “naked” DNA vaccination, a protocol with a variable outcome involving minimal adjuvant which is much less effective than adenovirus (reviewed in Ref. 4). Moreover, this earlier study was performed in a different mouse strain. Consequently, we cannot compare the lack of antibody differences between C57BL/6 /129 TSHR KO and wt mice vaccinated with the human TSHR DNA (19) with the findings in the present study, namely stronger responses in BALB/c TSHR KO vs. wt mice immunized with Ad-human TSHR A-subunit.

Mouse models of pemphigus and antineutrophil cytoplasmic autoantibody-associated glomerulonephritis/vasculitis have recently been successfully generated using desmoglein 3 and myeloperoxidase, respectively, KO mice (20, 21). Furthermore, stronger immune response to interphotoreceptor retinoid-binding protein (IRBP) and H/K APTase β-subunit, and development of exacerbated experimental autoimmune uveitis and gastritis by adoptive transfer of spleen cells have been demonstrated in the cognate antigen-deficient mice compared with wt mice (22, 23). Additionally, in a uveitis model (23), transplantation of the thymus from wt to IRBP KO mice reverted

<table>
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<th>Mouse strains</th>
<th>Immunization</th>
<th>No. of mice examined</th>
<th>No. of thyroiditis (% incidence)</th>
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<td>C57BL/6, control</td>
<td>Ad-mouse TSHR A-subunit</td>
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<td>0</td>
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<tr>
<td>1010 Ad-mouse TSHR A-subunit plus PC61</td>
<td>6</td>
<td>2 (17%)</td>
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<tr>
<td>B6 Control</td>
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<td>8</td>
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<td>1012 Ad-mouse TSHR A-subunit plus PC61</td>
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enhanced anti-IRBP immune response and exacerbated uveitis, and wt recipients of KO thymus developed stronger immune response to IRBP and severer uveitis. Overall, KO mice appear to be very useful to elicit strong immune responses to self-antigens.

It is worth noting here that thymic expression of self-antigens is also crucial for generation of antigen-specific CD4+CD25+ Treg, which are a main player for peripheral tolerance and control at the periphery self-reactive T cells escaped thymic negative selection (24). Thus, thymic tolerance likely involves elimination of both self-reactive effector T cells and generation of Treg. However, the development of humoral immune responses to the mouse TSHR in TSHR KO mice, but not in Treg-depleted wt mice, indicates that central tolerance, rather than Treg-mediated peripheral tolerance, plays a major role in tolerance to the mouse TSHR. Nevertheless, we cannot completely exclude a possibility of peripheral tolerance mediated by expression of the mouse TSHR in the thyroids, which may involve presentation of the TSHR antigen (particularly the shed TSHR A-subunit) (25) by immature dendritic cells in the regional lymph nodes of the thyroids (26).

Another interesting finding in the present study is the relatively poor cross-reactivity of antibodies elicited by the human A-subunit immunization for the mouse TSHR when measured by flow cytometry. This finding was unexpected because such antibodies generated in wt BALB/c mice effectively induce hyperthyroidism in a majority of

FIG. 5. TSHR antibodies in sera from immunized TSHR KO BALB/c mice measured by flow cytometry using CHO-mouse or -human TSHR cells. TSHR KO mice were left untreated (cont) or immunized twice with Ad-human or -mouse TSHR A-subunit and bled 2 wk after second immunization. TSHR antibodies were measured by flow cytometry (described in Materials and Methods) using CHO-human TSHR (A and C) and CHO-mouse TSHR (B and D). Values are % control of the mean fluorescence index (MFI) for individual mice.

FIG. 6. TSAb activities in sera from control and mouse A-subunit (A & B) or human A-subunit (C & D) immunized TSHR KO BALB/c mice measured by a bioassay using CHO-mouse (A & C) or -human (B & D) TSHR cells. Sera used in Fig. 5 were subjected to a TSAb assay (described in Materials and Methods). TSAb values (means of duplicated assays, % control and pmol/well) are shown for individual mice.
mice (2, 3). However, TSHR antibodies induced by immunization with either the human or mouse TSHR A-subunit were similarly effective in a TSAb bioassay using CHO cells expressing either of these two receptor species. Several amino acids on the human TSHR have been identified as contributing to the binding sites of stimulating (IRI-SAb2, IRI-SAb3, and M22, all of which also have TBI activities) and blocking (1H7 and RSR-B2) monoclonal anti-human TSHR antibodies (56T, 58K, 60I, etc.) (27, 28). All these amino acids are identical between the human and mouse TSHR (Fig. 1B), consistent with IRI-SAb2 and IRI-SAb3 also binding to the mouse TSHR (27). Overall, presently available data indicate that TSHR antibodies to the TSH binding site on the human TSHR can cross-react with the mouse TSHR in BALB/c mice.

Finally, although homology between human and mouse TSHR is relatively high, the Graves’ murine model using Ad-human TSHR A-subunit that we previously established may not be an ideal autoimmune disease model. Our present findings show that, rather than studying responses to a cross-reacting receptor (the human TSHR), immunization of TSHR KO mice with an adenovirus expressing the mouse TSHR A-subunit will be invaluable tools for dissecting responses to the autoantigen in mice, the mouse TSHR.

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