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Modeling thermal responses in human subjects following extended exposure to radiofrequency energy

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Abstract

Background: This study examines the use of a simple thermoregulatory model for the human body exposed to extended (45 minute) exposures to radiofrequency/microwave (RF/MW) energy at different frequencies (100, 450, 2450 MHz) and under different environmental conditions. The exposure levels were comparable to or above present limits for human exposure to RF energy.

Methods: We adapted a compartmental model for the human thermoregulatory system developed by Hardy and Stolwijk, adding power to the torso skin, fat, and muscle compartments to simulate exposure to RF energy. The model uses values for parameters for "standard man" that were originally determined by Hardy and Stolwijk, with no additional adjustment. The model predicts changes in core and skin temperatures, sweat rate, and changes in skin blood flow as a result of RF energy exposure.

Results: The model yielded remarkably good quantitative agreement between predicted and measured changes in skin and core temperatures, and qualitative agreement between predicted and measured changes in skin blood flow. The model considerably underpredicted the measured sweat rates.

Conclusions: The model, with previously determined parameter values, was successful in predicting major aspects of human thermoregulatory response to RF energy exposure over a wide frequency range, and at different environmental temperatures. The model was most successful in predicting changes in skin temperature, and it provides insights into the mechanisms by which the heat added to body by RF energy is dissipated to the environment. Several factors are discussed that may have contributed to the failure to account properly for sweat rate. Some features of the data, in particular heating of the legs and ankles during exposure at 100 MHz, would require a more complex model than that considered here.

Background

Heating of body tissues by radiofrequency (RF) energy is a mechanism for therapeutic as well as possible harmful effects of RF energy. Such effects may be produced by local changes in tissue temperature (for example, thermally induced changes in regional blood flow) and others may be systemic effects due to the additional thermal load on the body. Excessive exposure to RF energy can produce burns or other thermal damage to tissue, or, for whole body exposure, physiological stress resulting from excessive body heating.

Since the 1960s, exposure guidelines for human exposure to RF energy in effect in the United States and elsewhere [1,2] have been based in large part on animal studies. In particular, the limits in [1,2] for whole-body exposure are based on responses of animals subjected to whole-body exposures at levels that are sufficient to produce behavioral changes but not thermal damage to tissue. Because of the large interspecies differences in thermoregulation, the observed responses in the animals used for these studies (chiefly, rodents and primates) may not be representative of human responses under similar exposure conditions.

Until recently there has been almost a complete lack of data from humans exposed for extended times to RF energy under conditions that are relevant to setting exposure guidelines. Several recent studies at the John B. Pierce Laboratory in New Haven CT and the Air Force Research Laboratory (AFRL) at Brooks AFB, Texas by Adair and colleagues have measured thermoregulatory responses to extended (45 minute) RF exposures of human volunteers under controlled environmental conditions. These studies measured a variety of sensory and thermophysiological endpoints [3-6] in subjects exposed to RF energy at frequencies of 100, 450, and 2450 MHz. These studies are the first, and apparently only, measurements of physiological responses of humans exposed for extended periods to RF energy of substantial parts of their bodies. The tests were conducted under carefully controlled environmental conditions and at exposure levels well above present U.S. and international limits.

However, given the expense and difficulty of such studies, the amount of human data that can be obtained will necessarily be limited. The use of appropriate thermal models can extend the usefulness of such studies, to model thermophysiological responses of humans over broader ranges of environmental and exposure conditions than are feasible to study experimentally. Such a model must consider heat transfer at the local level and its modification by thermoregulatory responses.

A simple, and for its purposes quite successful, model of thermoregulatory responses of the body exposed to RF energy (during MRI imaging) was developed by Adair and Berglund in the late 1980s [7,8]. The model predicted changes in core and skin temperatures, sweat rate, and judgments of thermal sensation and discomfort that were very similar to measured data. The model, which had only two nodes, provided no information about regional thermoregulatory changes.

A far more detailed model was recently reported by Bernardi et al [9], who combined a detailed numerical calculation of the specific absorption rate (SAR, the rate of power deposition in tissue, units of W/kg) in the body from exposure to RF energy, with a detailed thermal model of the body including thermoregulatory changes in skin blood flow and sweating. This approach yields detailed information about the distribution of absorbed energy throughout the body but is computationally very intensive.

This present study evaluated a model of intermediate complexity, that of Hardy and Stolwijk [10]. While more recent thermal models for the human body are available [e.g. [11,12]], the Hardy-Stolwijk model was chosen for several reasons: it is a physiologically based model that was developed over a period of more than two decades and was validated by numerous human studies, and remains valid today. Unlike some of the more recent models, source code, model parameters, and extensive commentary are readily available [10].

The Hardy-Stolwijk model is complex, with several hundred parameters that were originally set by Stolwijk and colleagues for a "standard man" on the basis of thermophysiological studies, principally on male college students. This present study was developed as a baseline exercise, using the model with as little modification as possible, to compare its predictions with the data as reported in [3-6]. Extensions of the model, for example to adapt it for individual subjects or subdivide the compartments to account for the nonuniform exposure of the body surface to RF energy, were not attempted. As discussed below, the predictions of the model are nevertheless in reasonable agreement with the experimental data.

Methods

Source of data

We used data reported in [3-6], that described separate studies of human exposure to RF energy absorption at three different frequencies (100, 450, 2450 MHz) under identical test protocol. The data were reported as pooled responses measured in cohorts of 7 subjects, which included adults of both genders (approximately evenly distributed between males and females) and varying ages (21–69 years). The sex, age, height, mass, and DuBois skin surface area of the cohort members are tabulated in [3-6]. The studies are complex, and details of the experimental methods and exposure dosimetry are found in these references.

All studies employed the same protocol. Each individual test session started with a 30-min baseline period, followed by 45 minutes of RF or sham (no RF) exposure, and concluded with a 10 minute post-exposure baseline period. This sequence was repeated for each subject at three ambient temperatures (T_a) of 24, 28 and 31°C and, at each ambient temperature, at different exposure levels plus sham exposure. In all experiments, the relative humidity was 50 ± 10 %, and the air flowrate in the chamber was 0.35 m/sec. The subjects were seated, with a measured metabolic rate of 1.2 to 1.4 W/kg (compared to a basal metabolic rate of about 0.8 W/kg).

In each study, physiological data (including core and six skin temperatures, metabolic heat production, skin blood flow measured by laser-Doppler flowmetry, and local sweat rate measured by changes in dewpoint temperature) were recorded at several locations on each subject. Measurements subject to modeling included skin temperature in left upper back and central lower back, blood flow measured in the left upper back, and sweating rate measured in the left upper back. The core body temperature was measured in the esophagus at the level of the heart.

Exposure assessment and energy inputs to the model

The subjects were seated in an anechoic chamber and their backs exposed in the far field to RF energy from a microwave horn or dipole antenna (A dipole antenna mounted in a 90° corner reflector was used for both 450 and 100 MHz studies, while a standard gain horn was used for 2450 MHz.). The exposure (specific absorption rate, SAR) was determined in the original studies by a combination of computer modeling, and by thermal measurements on a "phantom" mannequin whose shape and bulk electrical characteristics were similar to those of the human body [13]; we used values of incident power density and SAR as provided in the original papers. In the discussion below, the cited exposure levels are in the area of highest exposure, which was located on the posterior aspect of the trunk. However, other parts of the body (posterior aspects of the head and upper arms) also received some exposure, depending on the frequency of the RF radiation. At 100 MHz, the entire body was exposed, yielding energy absorption throughout the body.

The energy deposition patterns in the body vary widely for RF energy at the three frequencies used in the Adair studies. The lowest frequency, 100 MHz, is close to an electrical resonance of the body of seated subjects, resulting in a deep and diffuse pattern of energy absorption. At the other frequencies, the wavelength of the radiation in tissue is smaller than body dimensions, and the energy is deposited in an exponentially decreasing pattern near the body surface. Consequently, the appropriate measure of exposure at 100 MHz is the SAR averaged over the whole body, while that at 450 and 2450 MHz is the SAR near the body surface. Table 1 summarizes the exposures at each of the three frequencies. It should be noted that all of these exposures exceed IEEE (Institute of Electrical and Electronics) and ICNIRP (International Commission on Non-ionizing Radiation Protection) exposure limits by varying amounts [1,2].

Table 1: Exposure Parameters Used With The Model

Frequency, MHz	Incident power densities, W/m^2 (peak field intensity in beam)	Peak surface specific absorption rate (SAR), W/kg	Total Power Added to Model, W *
100	40, 60, 80	0.26, 0.39, 0.52 (estimated whole body average SAR)	19, 29, 38 (based on 70 kg model)
450	240	7.7 (SAR at surface)	86 (based on 0.68 m^2 surface area of torso and parameters in Table 2)
2450	270, 350, 500, 700	5.9, 7.7,11, 14.4 (SAR at surface)	50, 64, 92, 128 (based on 0.68 m^2 surface area of torso and parameters in Table 2)

* Basal heat production 86 W

Table 2: Power absorbed per unit area in different body compartments⁺

Tissue (thickness, cm)	450 MHz ε*	Power (W/m^2)	2450 MHz ε*	Power (W/m^2)
Skin (0.3)	49-27j	0.09	38-10.7j	0.16
Fat (1.25)	11.6-3.3j	0.03	5.3-0.77j	0.03
Muscle (4.4)	56.7-32j	0.34	53-13j	0.08
Core	56.7-32j	0.07	53-13j	0.0
TOTAL		0.53		0.27

⁺ Calculated assuming an incident power density I_o = 1 W/m^2. ε* is the complex permittivity of the tissue (expressed as a real and imaginary part).

The Hardy-Stolwijk model divides the body into six segments (head, arms, hands, trunk, legs, feet), each of which is further subdivided into four concentric compartments (skin, fat, muscle, core). For the experiments involving 100 MHz radiation, all of the absorbed energy was assumed to be deposited into the core of the trunk; in reality the energy at this frequency is deposited in many regions of the body particularly in the lower legs and ankles, as well as knees and neck. To estimate the energy inputs into the different compartments for exposures at 450 and 2450 MHz, we calculated the SAR distribution for plane waves incident on a planar four-layer model. The top three layers had the same thickness as the skin, fat, and muscle compartments of the trunk in the Hardy-Stolwijk model. The fourth layer (corresponding to the core compartment) was assumed to be very thick (i.e. no reflections of waves from its rear surface were considered). The fraction of incident energy that is absorbed in each of these layers was obtained by solving the electromagnetic field equations for a plane wave incident on multilayer planes [14], whose dielectric properties were taken to be those of the respective tissues [15]. These calculations were verified using a finite element computer program (FEMLAB, Comsol AB, Stockholm Sweden). The results of these calculations are summarized in Table 2. The electromagnetic theory is described in detail in [14] and other standard textbooks and is not repeated here.

In the Hardy-Stolwijk model, there is no way to add heat only to the posterior surface of the trunk. Instead, we modeled a somewhat different exposure condition for the experiments involving 450 and 2450 MHz, corresponding to a situation in which the incident power was applied uniformly to the entire trunk. As a result, the total power absorbed in the torso compartment of the model was 3–4 times higher than absorbed in the torsos of the human subjects (This approximation was not used when simulating exposures at 100 MHz, for which the total absorbed RF power in the human subjects was added to the torso core segment).

This approximation can be justified for two main reasons. The two highest frequencies used, 450 and 2450 MHz, are above the electrical resonance frequency of the body and the energy incident on the trunk is generally deposited near the body surface. Under these conditions, the local temperature increase in the skin depends directly on the local SAR and only indirectly on the whole body SAR. Second, the total absorbed power in the human subjects (i.e. the whole body SAR) was comparable to or below the resting metabolic rate. As a result, thermoregulatory responses were modest; neither the model nor data showed noticeable changes in core temperature due to whole-body heating at any of the three frequencies. This approximation would be expected to be more successful in calculating the local increases in skin temperature than in predicting the rather small thermoregulatory responses to whole body heating. Alternative approaches, for example subdividing the torso compartment into posterior and anterior aspects, would further complicate the already very complex Hardy-Stolwijk model.

Implementation of model

We implemented the Hardy-Stolwijk model as described in [4], with the same parameter values described in that reference. The original FORTRAN code was translated into Matlab (The Mathworks, Natick MA). The full model as described in [4] includes feedback control that depends on the rate of temperature increase in each compartment, i.e. a form of derivative control. We found that including these rate dependent terms resulted in instabilities and apparent chaotic behavior in the model, which were presumably numerical in origin. In our work (as in [4]) the rate-dependent terms were set to zero.

The model was run to simulate 45-minute exposures at the appropriate levels, and at ambient temperatures of 24, 28, and 31°C, with the same relative humidity and air velocity as in the experiments. To ensure that the model had reached the steady state, calculations were run for a simulated three-hour period before exposure. The model ran in 15 seconds or less on a desktop PC with a 1 GHz processor.

Results and discussion

The discussion below will focus on thermophysiological responses at 31°C, which were generally the largest observed. At this temperature, most individuals would feel warm and a small addition of heat from RF energy would elicit much larger thermophysiological responses than would occur at lower ambient temperatures.

Under most of the experimental conditions, even at 31°C, only modest thermoregulatory responses were measured in the subjects. This was expected because for most exposures, the amount of RF power absorbed in the body was less than the resting rate of heat production. None of the exposures resulted in an appreciable change in core temperature or rate of metabolic heat production [3-6]. However, under some exposure conditions, particularly in the warmest environment (31° C), substantial increases in skin temperature were measured.

Skin temperature increase

Figures 1, 2, 3 show the calculated skin temperature in the trunk and core at each of the three irradiation frequencies, compared with pooled data from the experimental subjects. The model was quite successful in predicting these responses (from pooled data), even the *decrease* in the skin temperature at the lowest irradiation frequency.

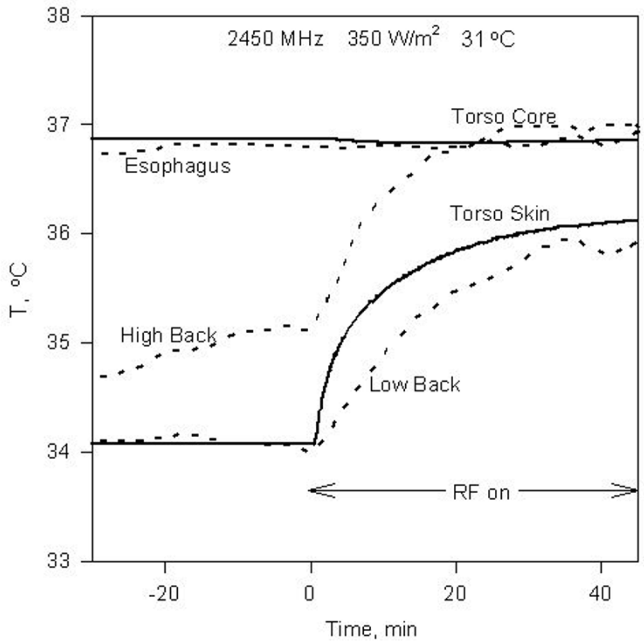

Figure 1
Changes in skin and core temperatures due to RF exposure at 350 W/m^2 at 2450 MHz, in a cohort of 7 human subjects, compared to the Hardy-Stolwijk model. Dotted lines: pooled skin temperatures from the upper and lower backs of 7 subjects, and esophageal temperature, from [3-6]. Solid lines: comparable predictions of the model. The RF energy exposure begins at t = 0 and lasts for 45 minutes.

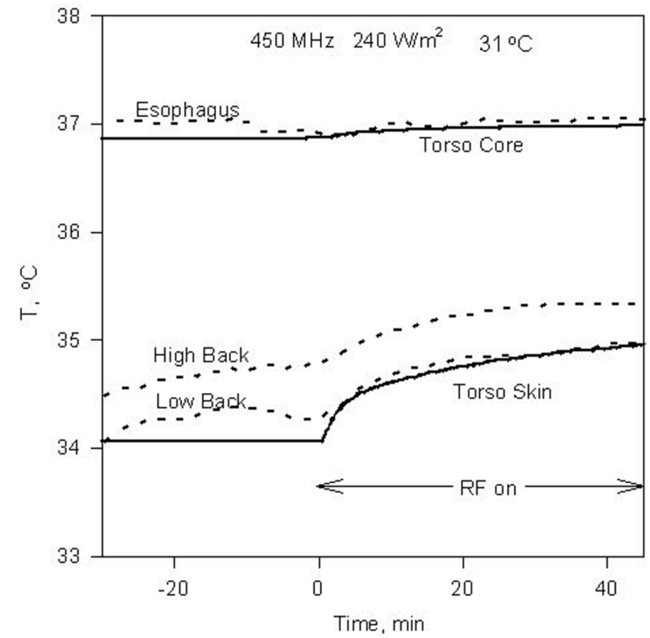

Figure 2
Same, exposure at 450 MHz.

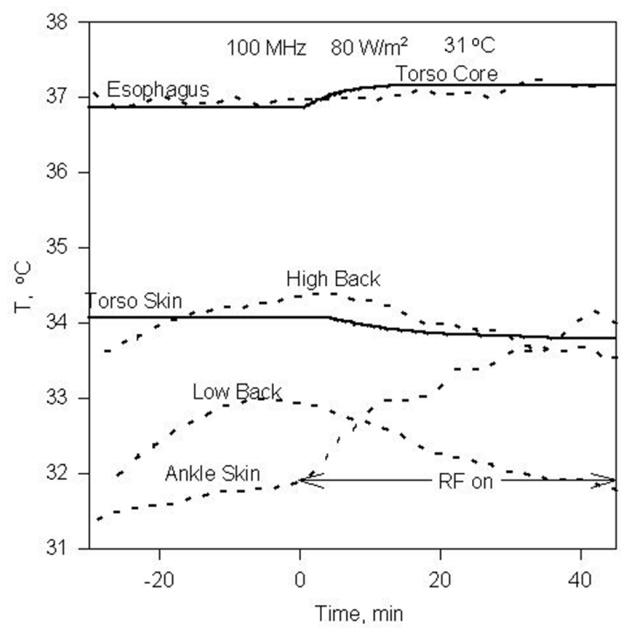

Figure 3
Same, exposure at 100 MHz. The subjects varied in each of the three experiments summarized in these figures.

This suggests that the model is basically correct in its treatment of heat flow through the skin, at least under conditions where thermoregulatory changes in the body are modest. It should be successful in predicting changes in skin temperature under more complex exposure conditions, including with multiple frequencies or complex on-off exposure parameters.

The model also provides insight into the mechanisms of heat flow through the skin subject to RF irradiation. Many studies have modeled the heating of tissue with RF energy using the bioheat equation, to investigate therapeutic applications and potential safety issues. It is clear from Table 4 that the transport of heat through the skin generated by RF energy takes place in the face of substantial background fluxes of energy due to thermophysiological processes. The relative magnitudes of these heat fluxes vary greatly with ambient temperature, and would not be predicted by a simple application of the bioheat equation.

Table 3: Energy flows in torso skin compartment after 45 minutes of RF exposure at 2450 MHz (350 W/m²). All energy flows expressed in watts. Positive numbers correspond to power deposited into skin compartment.

	24°C			28°C			31°C		
	RF Exposure	No RF	difference	RF Exposure	No RF	Difference	RF Exposure	No RF	difference
RF power into torso skin compartment	38.1		38.1	38.1		38.1	38.1		38.1
Metabolic heating in skin	0.5	0.5	0.0	0.5	0.5	0.0	0.5	0.5	0.0
Conducted into skin from fat	20.7	37.6	-16.9	9.1	25.7	-16.6	9.8	15.9	-6.2
Evaporative heat loss from skin	-3.7	-3.8	0.0	-4.2	-3.8	0.0	-22.5	-7.6	-14.9
Power loss by radiation and convective cooling	-55.5	-36.1	-19.4	-43.3	-24.9	-18.4	-30.6	-18.4	-12.2
Heat added to skin by blood flow	1.7	1.8	-0.1	3.2	2.5	0.7	4.9	9.6	-4.7
Net power into skin compartment*	1.8	0.0	1.7	3.4	0.0	3.8	0.2	0.0	0.1

*Net of power flows. Numbers may not sum to zero because of heat storage in skin and rounding errors

Table 4: Changes in Torso Skin Temperature, Torso Skin Blood Flow, and Sweat Rate in Torso

	Change in Torso Skin Temperature, °C		Blood Flow in Torso Skin		Sweat Rate In Back, mg/(min cm²)	
Exposure Conditions	Data*	Model	Data* Before/After 45 Min Exposure, arbitrary units	Model Before/After 45 Min Exposure, g/(100 ml tissue min)	Data* Before/ After 45 Min. Exposure	Model Before/ After 45 Min Exposure
2450 MHz 350 W/m² 31°C	1.9 (high back) 1.9 (low back)	2.0	70/105	4.5/11	0.1/0.4-0.6	0.03/0.09
450 MHz 240 W/m² 31°C	0.7 (high back) 0.5 (low back)	0.9		4.5/11	0.1/0.4	0.03/0.1
100 MHz 80 W/m² 31°C	-0.9 (high back) -1.3 (low back)	-0.3	60/60	4.5/10	0.2/0.7	0.03/0.1

*Mean of 7 subjects. The experimental measurements of blood flow were performed using a Doppler probe whose readings are proportional to flow velocity of blood near the skin surface (not volumetric flow rate). No data were reported for torso skin blood flow in the cited references for the experiments with 450 MHz RF energy exposures.

Skin blood flow and local sweat rates

Table 4 compares skin blood flow and sweat rates in the model, with experimental results. Unfortunately, it is not possible to compare quantitatively the measured and predicted blood flow rates in the skin. The experimental technique used to measure skin blood flow, laser-Doppler flowmetry, measures the flow velocity of erythrocytes near the skin surface, on an arbitrary instrumental scale. By contrast, the blood perfusion appears in the model as a volumetric flow, i.e. the volume of blood passing through a given volume of tissue per unit of time, which is a function of both flow velocity and vessel diameter. Consequently, Doppler measurements of increases in "skin blood flow" will underestimate the increases in volumetric perfusion if vasodilation occurs – which is the chief mechanism for increasing blood flow in the skin. Nevertheless, the predicted and measured increases in blood flow appear qualitatively similar.

The most striking failure in the model is its underprediction of sweat rates, by as much as a factor of 5 or more below measured sweat rates. (Table 4). In part, this may have an experimental explanation: sweat rates were measured at one point on the upper back (a region of high sweat production) using capsules with air flowing through them to collect all moisture. By contrast, the model calculates the rate of evaporative cooling averaged over the whole torso surface – a very different quantity. Indeed, at the highest measured sweat rates, assuming they existed over the whole torso and all the sweat were to evaporate, would correspond to a power loss of approximately 200 W/m² from the trunk skin compartment. This is unrealistically high considering that maximum rate of energy transfer to the skin was below 100 W/m^2 (2450 MHz, incident field intensity 350 W/m^2).

The Hardy-Stolwijk model is an improvement over the two-node models previously described by Adair and Berglund [7,8], in that it provides information about temperature changes in particular parts of the body (e.g. the trunk). However, some aspects of the data clearly require a still more complex approach. For example, the largest change in skin temperature in the subjects exposed to 100 MHz RF energy occurred in the legs and ankles (Fig. 3), due to the relatively high SAR at those locations. This could be accommodated in terms of the present model by adding energy to each of the 25 compartments to reflect the SAR distribution in the body.

Other useful refinements would be to subdivide the different compartments into dorsal and ventral aspects to allow variation in exposure in different body surfaces, and to vary the model parameters to account for individual variation among subjects. But this would add more adjustable parameters into an already very complex model, and create difficulties in validating the model.

Considered as a model for heat transfer, the Hardy-Stolwijk model is clearly very successful for predicting thermal responses of the body to RF irradiation. The experiments we modeled, however, were very easy tests, given the modest thermoregulatory responses at the levels of RF energy exposure that were employed in the experiments. The total absorbed power in the subjects was below 40–80 W, compared to a metabolic rate in the seated subjects of 120–150 W.

A more critical test would employ higher irradiation intensities, or more extreme environmental conditions. Such experiments would require exposure levels far above present exposure limits, and would be unlikely to be approved by institutional review boards.

List of abbreviations

ICNIRP International Commission on Nonionizing Radiation Protection

IEEE Institute of Electrical and Electronics Engineers, Inc.

SAR Specific Absorption Rate

Authors' contributions

ERA supplied the data and was chiefly responsible for the interpretation of the thermophysiological data; KRF developed and ran the model. Both authors read and approved the final manuscript.

Disclaimer

The views expressed in this article are those of the authors and do not reflect the official policy or position of the U. S. Air Force, Department of Defense, or the U.S. Government. Trade names of materials and/or products or nongovernmental organizations are cited as necessary for precision. These citations do not constitute official endorsement or approval of the use of such commercial materials or products.

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