Morphological and functional relationships with ultrasound measured muscle thickness of the upper extremity and trunk

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Abstract

Unless a subject's muscle is relatively small, a single image from a standard ultrasound can only measure muscle thickness (MT). Thus, it is important to know whether MT is related to morphological and functional characteristics of individual muscles of the extremity and trunk. In this review, we summarize previously published articles in the upper extremity and trunk demonstrating the relationships between ultrasound-measured MT and muscle morphology (cross-sectional area, CSA and muscle volume, MV) and muscular or respiratory function. The linear relationship between MT and muscle CSA or MV has been observed in biceps brachii, triceps brachii, pectoralis major, psoas major, and supraspinatus muscles. Previous studies suggest that MT in the upper arm and trunk may reflect muscle CSA and MV for the individual muscles. Unfortunately, few studies exist regarding the functional relationship with ultrasound MT in the upper extremity and trunk. Future research is needed to investigate these findings further.

Keywords: **Ultrasonography, prediction, anatomical muscle cross-sectional area, muscle volume**

Ultrasound 2014; **22**: 229–235. DOI: 10.1177/1742271X14554678

Introduction

Approximately 50 years ago, Ikai and Fukunaga[1] reported the first ultrasound study to measure muscle cross-sectional area (CSA) of the upper arm muscle (biceps brachii) using a specially designed ultrasound apparatus, called a round compound scanner. Compared to manual measurement using cadaver arms, the ultrasound-measured muscle CSA differs by only 3.4%.[2] A quarter century after the first ultrasound study, Sipila and Suominen[3] examined the differences in quadriceps muscle CSA between ultrasound scans and computed tomography (CT) scans. They used a compounding technique of ultrasound images, but only a half-round compound scanner, to assess the quadriceps CSA and found that the ultrasound muscle CSA was 30% lower than the CT-measured value at the same site.[3] Over the last 10 years, a limited number of studies[4–7] have evaluated limb muscle CSA using a technique of compounding ultrasound images. Unfortunately, at this moment, the ultrasound compounding technique to assess muscle CSA is not widely used, which may be due to it being a cumbersome procedure.

Without a small muscle, a single image from a standard ultrasound can only measure muscle thickness (MT), but not muscle CSA.[8,9] Therefore, it is important to know whether MT is related to anatomical muscle CSA or muscle volume (MV) in an individual muscle of the extremity and trunk. If MT is strongly related to muscle CSA and MV, it may not be necessary to measure muscle CSA using a compounding technique, which is a cumbersome process. Recently, we reported in a review manuscript the relationships between ultrasound measured MT and magnetic resonance imaging (MRI) or CT-measured muscle CSA or MV in the lower extremity (Abe et al., unpublished article). In the upper leg muscles, a linear relationship between MT and muscle CSA or MV has been observed in the quadriceps ($r = 0.91$), adductor ($r = 0.95$), and hamstring ($r = 0.87$) muscles. Similar results are observed in the lower leg, in that anterior as well as posterior lower leg MT may reflect muscle CSA and MV of the lower leg muscles ($r = 0.70$–0.91), although there are a limited number of studies. In addition, adequate validity as well as reliability is necessary if ultrasound measurements are to be used as measures of muscle size. In this review, we first discuss validity and reliability of MT measurements in the extremity and trunk muscles. Second, we summarize previously published articles in the upper extremity and trunk demonstrating the relationships between ultrasound measured MT and MV measured using MRI scans. The relationship between ultrasound MT and muscular and physical function are also summarized. Meanwhile, for information on generation of conventional ultrasound imaging and also architectural and morphological features during muscle contraction, see the review article by Whittaker and Stokes.[10]

In this review, the interpretation of correlation coefficients was defined as follows: 0.00–0.25 indicated no correlation, 0.26–0.49 indicated low correlation, 0.50–0.69 indicated moderate correlation, 0.70–0.89 indicated high (strong) correlation, and 0.90–1.00 indicated very high (excellent) correlation.[11]

Literature search and inclusion criteria

A typical online search using MEDLINE, CINAHL, Web of Science, and SPORTDiscuss was performed with the following keywords and phrases to obtain relevant articles: ''ultrasound muscle thickness'' AND ''upper extremity'' OR ''trunk'' OR ''arm'' AND/OR ''muscle CSA'' OR ''muscle volume'' AND/OR ''strength'' OR ''function''. References from pertinent articles and the name of the authors cited were cross-referenced to locate any further relevant articles not found with the initial search. To be included, a study needed to meet the following criteria: (a) Main outcome measure: the study needed to measure muscle thickness of the upper body muscles using a B-mode ultrasound. (b) Secondary outcome measures: the study needed to investigate muscle CSA and/or MV measured by MRI or CT scan, isometric and/or isokinetic muscular strength and/or physical and respiratory functions. (c) Reliability data: the study needed to report a single intrarater and/or interrater reliability value in the upper extremity and trunk muscles but not a range of those values. (d) Language: the search was limited to original research that was written in English. Furthermore, we discuss the validity of ultrasound measurements, including the articles which were not collected by means of the aforesaid online search procedures.

Validity of ultrasound MT measurements

The validity of MT measurements in the limb and trunk muscles is presented in Table 1. Three cadaver dissection studies revealed that high validity was observed with the ultrasound MT measurement. For example, Fukunaga and colleagues[12] investigated the validity of ultrasound measurements at the upper arm, forearm, thigh and abdomen using a human cadaver. They reported that the difference between ultrasound and manual measured values (ultrasound minus manual) was −0.06 cm for forearm, −0.04 cm for upper arm posterior, −0.03 cm for thigh anterior, and −0.02 cm for abdomen. A very high correlation ($r = 0.996$, $p < 0.001$, $n = 53$) was observed between ultrasound and manual measured MT when pooled data of all measured sites were used. Kawakami et al.[13] and Narici et al.[14] also reported that ultrasound measurements differed from manual measurements by less than 0.1 cm for MT. Similarly, two MRI studies[15,16] reported excellent validation data for measuring MT in the shoulder (deltoid, $r = 0.98$ and supraspinatus, $r = 0.96$) and abdominal muscles (transversus abdominis, $r = 0.93$ and internal oblique, $r = 0.93$). O'Sullivan et al.[17] investigated the relationship between ultrasound- and MRI-measured MT at the lower, middle, and upper portion of the trapezius muscle and reported that a good correlation was observed between measurements of lower trapezius MT at the level of T8 ($r = 0.77$, $p < 0.001$). A fair correlation was also observed between measurements of upper trapezius at the level of C6 ($r = 0.52$, $p < 0.001$). However, no significant correlation was found with measurements of middle trapezius MT ($r = 0.25$, $p = 0.16$). They explained some reasons for the lack or relatively low correlations observed in upper and middle portions of trapezius muscle. An important reason is that body posture differed between ultrasound scans (prone) and MRI scans (supine) and measured MT may

Table 1 Validity of ultrasound muscle thickness measurements: comparison between ultrasound-measured muscle thickness and manual measurement using cadavers or MRI-measured muscle thickness

	Sample or subjects			Mean and SD (mm)				
Measured site	**Number**	**Age range**	**Reference Method**	**Ultra**	**Reference**	**Mean Diff (mm)**	***r***	**Authors**
Triceps brachii	$N = 1$	71 years	Cadaver	22.5 (9.8)	22.9 (9.6)	0.4	0.99	Fukunaga et al.[12]
Forearm				15.8 (1.5)	16.4 (1.7)	0.6		
Abdomen				7.3 (1.5)	7.5 (1.5)	0.2		
Quadriceps				10.3 (2.5)	10.5 (2.3)	0.3		
Hamstring				26.1 (12.3)	26.6 (12.0)	0.5		
Triceps brachii	$N = 3$	73–84 years	Cadaver	17.5	17.8	0.8	NR	Kawakami et al.[13]
Gastrocnemius (proximal)	$N = 1$	62 years	Cadaver	13.3	14.0	NR	NR	Narici et al.[14]
Deltoid	$N = 6$	24–51 years	MRI	NR	NR	1.5	0.98	Dupont et al.[15]
Supraspinatus				NR	NR	1.4	0.96	
Transversus abdominis	$N = 13$	21 ± 2 years	MRI	0.68	0.68	NR	0.93	Hides et al.[16]
Internal oblique				1.54	1.57	NR	0.93	
Lower Trapezius (T8)	$N = 18$	21–42 years	MRI	4.0 (1.2)	3.8 (1.4)	NR	0.77	O'Sullivan et al.[17]
Middle Trapezius (T1)				4.3 (0.8)	5.7 (1.4)	NR	0.25	
Upper Trapezius (C6)				5.0 (1.6)	6.2 (2.8)	NR	0.52	

NR: not reported; *SD*: standard deviation; *MRI*: magnetic resonance imaging; *Ultra*: ultrasound.

not be the same due to compression by the body. Therefore, the results from the previous cadaver and MRI studies suggest that ultrasound measured MT may be a valid method for estimating muscle size in the upper limbs and trunk.

Reliability of ultrasound MT measurements

The reliability of upper extremity and trunk muscles was reported by intrarater and inter-rater reliability coefficients and is found in Table 2. The standard error of the measurement (SEM) and minimal difference were also reported when possible. While intraclass correlation coefficient (ICC) is a relative measure of reliability, the SEM is a measure of absolute reliability. Absolute reliability concerns the consistency of scores of individuals, whereas relative reliability concerns the consistency of the position or rank of individuals in the group relative to others.[18] SEM and minimal difference calculations are important because ICC values are dependent upon between-subject variability. If subjects differ very little from each other, ICC values will be small even if the test–retest variability is small. In addition, if subjects differ substantially from one another, ICC values can be large even if test–retest variability is large.[18]

When examining the results of different studies, reported estimates of reliability were high to very high except for one study.[19–30] With the exception of two studies,[20,27] the reported intrarater correlation coefficients (ICC) among studies ranged between 0.84 and 0.99. Thoirs and English[20] reported high test–retest reliability in the

Table 2 Intrarater and interrater reliability of ultrasound muscle thickness (MT) measurements each measured site

					Reliability and Precision				
Measured site	**Subject number**	**Posture and state of MT testing**		**Device**	**ICC**	**95% CI**	**SEM (cm)**	**MD (cm)**	**Authors**
Intrarater reliability									
Anterior upper arm	$N = 10$	Standing	Resting	Aloka	0.98	–	–	–	Miyatani et al.[19]
Posterior upper arm					0.99	–	–	–	
Anterior upper arm	$N = 18$	Standing	Resting	Nanshan	0.89	0.79–.94	–	–	Thoirs and English[20]
		Supine	Resting		0.84	0.71–.92	–	–	
Posterior upper arm	$N = 18$	Standing	Resting		0.91	0.83–.95	–	–	
		Prone	Resting		0.84	0.80–.94	–	–	
Anterior upper arm	$N = 15$	Standing	Resting	Aloka	0.88	–	0.08	0.22	Abe et al.[21]
Posterior upper arm					0.96	–	0.08	0.22	
Forearm	$N = 18$	Standing	Resting	Nanshan	0.78	0.60–.88	–	–	Thoirs and English[20]
		Supine	Resting		0.75	0.56–.87	–	–	
Forearm (radius)	$N = 9$	Standing	Resting	Aloka	0.99	–	0.03	0.09	Abe et al.[22]
Forearm (ulna)					0.99	–	0.03	0.07	
Transversus abdominis	$N = 9$	Supine	Resting	Sonosite	0.93	0.75–.99	0.03	–	Teyhen et al.[23]
Rectus abdominis	$N = 18$	Standing	Resting	Nanshan	0.87	0.75–.93	–	–	Thoirs and English[20]
		Supine	Resting		0.94	0.88–.97	–	–	
Transversus abdominis	$N = 30$	Supine	Resting	Sonosite	0.94	0.87–.97	0.02	–	Koppenhaver et al.[24]
			Contracted		0.93	0.86–.97	0.04	–	
Lumbar multifidus	$N = 30$	Prone	Resting		0.98	0.95–.99	0.09	–	
			Contracted		0.97	0.94–.99	0.11	–	
Lumbar multifidus	$N = 8$	Prone	Resting	Sonosite	0.85	–	–	–	Kiesel et al.[25]
Lumbar multifidus, L2/3	$N = 10$	Prone	Resting	GE	0.89	0.72–.97	0.13	–	Wallwork et al.[26]
Trapezius	$N = 16$	Sitting	Resting	Pie Data	0.67	0.23–.88	0.10	–	Bentman et al.[27]
Supraspinatus	$N = 10$	Sitting	Resting	GE	0.91	0.80–.97	–	–	Yi et al.[28]
Gluteus maximus	$N = 16$	Prone	Resting	GE	0.99	0.97–.1.0	–	–	Ikezoe et al.[29]
Gluteus medius					0.99	0.97–.1.0	–	–	
Gluteus minimus					0.97	0.90–.99	–	–	
Psoas major					0.97	0.91–.99	–	–	
Psoas major (right)	$N = 9$	Prone	Resting	Aloka	0.98	0.90–.99	–	–	Takai et al.[30]
Interrater Reliability									
Transversus abdominis	$N = 30$	Supine	Resting	Sonosite	0.89	0.78–.95	0.03	–	Koppenhaver[24]
			Contracted		0.91	0.79–.96	0.04	–	
Lumbar multifidus	$N = 30$	Prone	Resting		0.88	0.63–.95	0.21	–	
			Contracted		0.93	0.85–.97	0.17	–	
Trapezius	$N = 16$	Sitting	Resting	Pie Data	0.81	0.63–.92	0.09	–	Bentman et al.[27]
Supraspinatus	$N = 25$	Sitting	Resting	Esaote	0.86	0.77–.92	–	–	Schneebeli et al.[31]

ICC: intra- or inter-class correlation coefficient; CI: confidence interval; SEM: standard error of measurement; MD: minimum difference.

upper arm and abdomen when subjects were measured in both standing and lying positions (ICC, 0.84–0.94). However, a relatively low ICC value (0.75) was observed at the lateral forearm when subjects were measured in a lying position. In the lateral forearm, two MTs were measured as the perpendicular distance between the subcutaneous adipose tissue–muscle interface and muscle–bone interface of the radius (forearm-radius MT) and ulna (forearm-ulna MT). Recently, Abe and colleagues[21] reported ICC, SEM, and minimum difference from nine middle-aged subjects for forearm-radius MT and forearm-ulna MT. The authors indicated that ICC and SEM were 0.99 and 0.03 cm for forearm-radius MT and 0.99 and 0.03 cm for forearm-ulna MT (Table 2). Six studies reported both ICC and SEM values, and the results indicate that the posterior trunk muscles may have a higher SEM than that of the arm and abdominal muscles.

Three studies[24,27,31] reported inter-rater reliability in the trunk muscles and the values demonstrated high and very high agreement (ICC, 0.81 and 0.93). All ICC estimates of intrarater and inter-rater reliability for the repeated measurements were greater than 0.81, except two studies which measured MT in the trapezius (ICC, 0.67) and forearm (ICC, 0.75–0.78).

Association between MT and muscle CSA or MV

Correlations between ultrasound-measured MT and the corresponding portion of MRI-measured muscle CSA or MV are presented in Table 3. The linear relationship between MT and muscle CSA or MV has been observed in the biceps brachii,[19,32] triceps brachii,[19] pectoralis major,[33] psoas major,[30] and supraspinatus[28] muscles. For example, Miyatani and colleagues[19] found a high correlation between ultrasound MT and MRI-measured MV in the biceps brachii ($r = 0.893$, $p < 0.05$, $n = 14$) and triceps brachii ($r = 0.734$, $p < 0.05$, $n = 14$) muscles in men aged 23–40 years. When combined with upper arm length (LL), the coefficient of determination between MV and MT × LL (biceps, $R^2 = 0.866$, SEE = 22.9 cm^3 (7.8%) and triceps, $R^2 = 0.803$, SEE = 40.4 cm^3 (10.2%)) was higher than when using MT alone. Recently, Akagi et al.[32] developed a prediction equation of the biceps brachii MV applicable to men and women with a wide range of ages. The subjects were randomly separated into either a validation ($n = 80$, 38 men and 42 women) or a cross-validation ($n = 67$, 34 men and 33 women) group. They reported that a multiple regression equation to predict MV of the biceps brachii using MT, upper arm length, gender and age as independent variables was validated ($R^2 = 0.897$, SEE = 21.2 cm^3 (11.8%)) and cross-validated ($R^2 = 0.909$, SEE = 19.9 cm^3 (10.9%)). In the upper arm muscles, MV appears to be highly correlated with MT measured by ultrasound. Unfortunately, other major muscle groups in the upper extremity such as forearm have not been investigated.

For the trunk muscles, Yasuda and colleagues[33] reported a very high correlation ($r = 0.92$, $p < 0.001$, $n = 20$) between ultrasound measured pectoralis major MT and the corresponding portion of MRI-measured muscle CSA in young

Table 3 Correlations between ultrasound-measured muscle thickness (uMT) and MRI-measured muscle cross-sectional area (CSA), muscle volume (MV) or muscle thickness ($_{\text{MRI}}$MT) in the upper extremity and trunk

Authors	Year	Reference Variable	Subject Number	Subject Age Range	Reference Method	Posture of MT Testing	Regressions	r
Miyatani et al.[19]	2004	MV	$N = 27$	23–40 years	MRI	Standing	Biceps brachii MV (cm^3) = 113.7 × biceps uMT + 11.6 × LL − 443.7	0.93
							Triceps brachii MV (cm^3) = 90.3 × triceps uMT + 30.5 × LL − 908.2	0.90
							uMT, muscle thickness at 60% of upper arm length (centimeter); LL, upper arm length (centimeter)	
Akagi et al.[32]	2010	MV	$N = 80$	19–77 years	MRI	Standing	Biceps brachii MV (cm^3) = 60.8 × biceps uMT + 6.48 × LL − 0.709 × age (year) + 51.4 × gender (male = 1, female = 0) − 187.4	0.95
							uMT, muscle thickness at 60% of upper arm length (centimeter); LL, upper arm length (centimeter)	
Yasuda et al.[33]	2010	CSA	$N = 20$	NR, young	MRI	Standing	Pectoralis major uMT vs. CSA	0.92
Takai et al.[30]	2011	CSA	$N = 11$	21–25 years	MRI	Prone	Psoas major CSA (cm^2) = 5.28 × psoas major uMT − 7.99	0.95
							uMT, muscle thickness at L4–L5 (centimeter)	
Yi et al.[28]	2012	CSA	$N = 10$	59 ± 9 years	MRI	Sitting	Supraspinatus uMT vs. CSA	0.76

NR: not reported; *MRI*: magnetic resonance imaging; *MT*: muscle thickness.

men. Similar results were also reported with the psoas major muscle in that CSA measured by MRI is highly ($r = 0.95$, $p < 0.05$, $n = 11$) correlated to MT of the psoas major measured by ultrasound.[30] In addition, Yi et al.[28] found a high correlation ($r = 0.76$, $p = 0.01$, $n = 10$) between ultrasound measured supraspinatus MT and MRI-measured supraspinatus muscle CSA in hemiplegic patients. Although there are a limited number of studies, the results are similar to MT of the upper extremity in that MT in the trunk may reflect muscle CSA and MV of the individual trunk muscles.

Anatomically, the transverse plane of the limb muscle appears as a circle centered at the bone. The equation to calculate the area of a circle is $\pi \times r^2$, so it may be that MT (or MT^2) is useful for predicting muscle CSA. Additionally, a combination of MT with limb length may be useful for estimating MV. These hypotheses are accepted by the results from previous studies showing that there are strong correlations between MT of the upper extremity as well as lower extremity and the corresponding portion of MRI-measured muscle CSA and MV. However, there are variously shaped muscles (e.g., broad muscle) in the trunk. Thus, it is unknown whether MT relates to muscle CSA and MV in all the trunk muscles. It is clear that future research is required to investigate these findings further.

Association between MT and muscle function

Muscle function is defined as the ability of a muscle to generate force or power, resulting in motion of the body. Thus, we focused on static and dynamic muscular strength and its related body movement and performance. As described above, ultrasound measured MT is closely associated with anatomical muscle CSA and MV in the upper arm and some trunk muscles. From a physiological standpoint, anatomical muscle CSA and MV are valuable predictors of muscular strength and power output.[34,35] Therefore, there is expected to be a good relationship between MT and muscular function. Correlations between ultrasound MT and muscular and respiratory functions are presented in Table 4. At this time, very few studies have been published. For example, Ichinose and colleagues[36] investigated the relationship between morphological and functional aspects of the triceps brachii muscle in young athletes. The triceps muscle CSA was estimated using ultrasound MT ($CSA = \pi \times [MT/2]^2$). They reported that the estimated triceps muscle CSA was significantly correlated to isokinetic elbow extension torque at 60°/s ($r = 0.702$, $p < 0.05$) and 180°/s ($r = 0.776$, $p < 0.05$). Abe and colleagues[22] investigated the relationship between ultrasound-measured forearm MT from the radius and ulna bone interface and handgrip strength in old men and women. Forearm-ulna MT was correlated to handgrip strength in both sexes ($r = 0.524$, $p < 0.01$ for men and $r = 0.475$, $p < 0.05$ for women). However, forearm-radius MT was significantly correlated to handgrip strength in women only ($r = 0.286$, n.s. for men and $r = 0.439$, $p < 0.05$). They reported that the reason for this apparent sex difference is unknown, but it may be related to the location and muscle size of the major flexor muscles in the forearm. Three major muscles (*flexor digitorum profundus, flexor digitorum superficialis, flexor pollicis longus*) are the prime movers of the digits, and forearm-ulna MT mainly includes two muscles (*flexor digitorum profundus, flexor digitorum superficialis*), which produce flexion movement for the middle phalanges of the fingers. The difference between forearm-ulna MT and forearm-radius MT is greater in men (forearm-ulna minus forearm-radius MT, 1.86 cm) than in women (1.58 cm). Handgrip strength may be associated with greater forearm-ulna MT in men, which involves the major flexor muscles. While in women, development of the forearm-ulna MT is lower compared with men and the contribution to handgrip strength may not be different from the forearm-radius MT. In addition, handgrip strength is generated from a combination of the intrinsic and extrinsic hand muscles and the forearm MT is an index of the extrinsic muscle, this factor may have influenced the low to moderate correlation coefficients observed between forearm MT and handgrip strength (Table 4). However, Misuri and colleagues[37] investigated the relationship between changes in abdominal MT and respiratory function in young men. They reported that during maximum expiratory maneuvers, transversus abdominis, internal oblique, and rectus abdominis thickened similarly. A significant correlation was found between MT of the transversus abdominis and gastric pressure in all subjects.

Table 4 Correlations between ultrasound-measured muscle thickness and muscular and respiratory functions

Authors	Year	Subject Number	Subject Age range	Measurement Variables	Exercise Mode	Posture and State of MT Testing	Tested Muscle	*r*
Ichinose et al.[38]	1998	*N* = 61	NR, young	Elbow extension	Isok 60°/s	Standing/resting	Triceps brachii	0.70
					Isok 180°/s			0.78
Abe et al.[21]	2014	*M* = 32	70–79 years	Handgrip	Isometric	Standing/resting	Forearm (radius)	0.29
							Forearm (ulna)	0.52
		W = 21	70–83 years	Handgrip	Isometric	Standing/resting	Forearm (radius)	0.44
							Forearm (ulna)	0.48
Misuri et al.[37]	1994	*M* = 6	26–36 years	Gastric pressure (Respiratory function)	Progressive expiratory effort	Sitting/contracted	Transversus abdominis	0.63–0.82

M: men; *W*: women; *MT*: muscle thickness; *Isok*: isokinetic contraction.

The results suggest that the transversus abdominis seems to be the major contributor in generating abdominal expiratory pressure during progressive expiratory efforts. Unfortunately, few studies exist regarding the functional relationship with ultrasound MT in the upper extremity and trunk. Future research is needed to investigate these findings further.

Conclusion

The results of previous studies suggest that ultrasound MT measurements may offer a valid and reliable method for estimating muscle size in the trunk and upper extremity. The linear relationship between ultrasound-measured MT and MRI-measured muscle CSA or MV has been observed in biceps brachii, triceps brachii, pectoralis major, psoas major, and supraspinatus muscles. These results suggest that MT in the upper arm and trunk may reflect muscle CSA and MV for the individual muscles. Although there are a limited number of studies, MT is a variable predictor for evaluating elbow joint and handgrip strength and respiratory function.

DECLARATIONS

Competing interests: The authors have no conflicts of interest to declare
Funding: This work received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors
Ethical approval: Not applicable
Guarantor: TA
Contributorship: All authors (TA, JPL, RST, and ML) searched the previous studies. TA summarized the data describing the previous studies and wrote the first draft of the manuscript. All authors reviewed and edited the manuscript and approved the final draft.

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