Tear evaporation rates: What does the literature tell us?

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Abstract:

Purpose: A previous literature review reported tear evaporation rates (TERs) from studies conducted on rabbits and humans between 1941 and 2003. Closer examination of the presented data revealed inaccuracies in the reporting of some values. This paper presents updated tables of TERs using values from the original papers cited in the review, in addition to incorporating new studies published between 2003 and 2016.

Methods: A copy of each paper cited in the literature review was obtained and checked against the evaporation rate reported in the review. If the expected value could not be found in the cited paper, other papers by the same author were consulted to see if the value had been reported elsewhere. A PubMed and Scopus database search was conducted to find papers published on tear evaporimetry since 2003.

Results: Two new tables of TERs were created, based on the values reported by the original author. To aid in interpretation, the majority of results are expressed in units of x 10^{-7} g/cm^2/sec. Where it was not possible to convert these values, some values are expressed as x 10^{-7} g/sec, x 10^{-7} g/sec/eye or W/min.

Conclusions: Two new tables of TERs have been compiled to provide an accurate representation of the values reported in the original papers. These tables can be used as a point of reference for other researchers to compare their results.

Keywords: tear evaporation; dry eye; meibomian gland dysfunction; evaporimetry

Introduction:

Dry eye disease is estimated to affect between 5-35% of the population [1]. The 2017 report of the Tear Film and Ocular Surface Society (TFOS) International Dry Eye WorkShop (DEWS) II classified dry eye into three main types: aqueous deficient (ADDE), evaporative (EDE), and mixed [2]. Meibomian gland dysfunction (MGD) is the leading cause of EDE, and is commonly encountered in clinical practice. Humans with an absent lipid layer, or an abnormal coloured fringe tear lipid pattern when viewed with specular reflection, have a four-fold increased rate of evaporation [3].

Evaporimetry is used to indirectly measure the rate of evaporation of the aqueous component from the tear film. The rate of water loss from the exposed ocular surface is typically investigated using temperature and humidity sensors incorporated within a goggle, of which there are two main designs - closed-chamber and open-chamber. Closed-chamber devices [4-9] are fully enclosed and are usually housed within a swimming goggle. This prevents the ocular surface from interacting with the external environment. Open-chamber devices [10, 11] have a hole within the instrument which exposes the sensor to the ambient surroundings throughout the measurement. Many evaporimeters have also incorporated ventilation so that air of a known relative humidity (RH) and/or air flow can be added to the chamber [4-6, 8, 12].

The most common closed-chamber device reported in the literature [8, 13-26] was designed by Mathers [8] and includes a dry air ventilation system (Figure 1). The majority of published literature available on an open-chamber, unventilated evaporimeter was conducted with the ServoMed EP1 or EP3 (ServoMed, Sweden), which was a dermatological device that was modified

for use on the eye [3, 10, 27-43]. More recently, spectral interferometry [44-46] and infrared thermography [47-49] have been used to estimate the rate of tear film evaporation. Currently, the only commercially available evaporimeter is an unventilated, closed-chamber device, the Eye-VapoMeter (Delfin Technologies, Finland), which was recently validated for ocular use [9].

Since a standardised and accepted method of measuring and reporting evaporimetry does not yet exist, researchers have found a variety of ways of expressing the human tear evaporation rate (TER) (Figure 2). Evaporation rates have most frequently been expressed in units of x 10^{-7} $g/cm^2/sec$ or $g/m^2/hr$. Modified dermatological devices that were originally designed to measure water loss from the skin, such as the Eye-VapoMeter [9, 50-52], the ServoMed EP1 or EP3 [10, 32] and the Tewameter [11], calculate rates of evaporation in units of $g/m^2/hr$. Other researchers have reported TER in units of $\mu l/min$ [8, 13-15, 42-44, 53], $\mu l/cm^2/min$ [16-23], $\mu m/min$ [44-46, 54], W/m^2 [47, 48] and W/min [49]. Since there are a number of different ways of reporting TER, this leads to difficulty when comparing and interpreting the values reported between devices and varying ocular conditions or environments.

Mathers [55] published a literature review in 2004 that discussed the reported values of TER from the ocular surface available at that time. The first table of the review summarised the evaporation rate of 18 studies conducted on rabbits and humans between 1941 and 2003. The table included TER for humans with healthy, normal eyes and diseased eyes, with conditions such as dry eye or MGD.

Closer examination of the table revealed some inaccuracies between the values reported by the review [55] and the original values published by the cited author. These errors could have an impact on the validity of the summarised data, and its use as a point of reference for researchers and clinicians. Since 2003, many other studies have been published on normal and dry eye TER.

The aim of this paper is to present an updated summary of published tear evaporation rates (TERs) for healthy human eyes and dry eye or diseased eyes from 1980 to 2017. The manuscripts cited by Mathers [55] will serve as a synopsis of studies conducted between 1947 to 2002. The intention is to incorporate the original TER as a single unit of measurement (x 10^{-7} g/cm^2/sec), to aid in comparison of the reported values.

Methods

A copy of each paper cited by Mathers [55] in his first table, that listed the TER for normal and dry eyes, was obtained via online databases, the university library, or requested through Scholars Portal RACER Inter-library Loan. Papers that were not originally written in English were translated by colleagues that were fluent in German or Japanese. Each cited paper was checked against the values as reported by Mathers [55] for accuracy of transferral. If the specified rate of evaporation could not be found in the paper cited by Mathers, then other papers with summaries of TER [56, 57] and PubMED were consulted, to determine if an alternative source could be found in case a paper had been inadvertenly cited incorrectly.

PubMED and Scopus databases were searched to locate papers published between 2003 and 2017 that contained references to evaporimetry or tear evaporation. Other papers [56-60] listing tables

of TER were also consulted to identify additional references. Copies of these papers were obtained in the same manner as described above.

Attempts were made to convert all the original author's TER values to units of x 10^{-7} g/cm^2/sec to aid in easy comparison and interpretation of the reported values. TERs stated in g/m^2/hr were converted to units of x 10^{-7} g/cm^2/sec by dividing the first value by 3.6 [58, 59]. Units of μl/cm^2/min were converted by dividing the reported TER value by 60000 (based on the assumption that 1000μl is equivalent to 1g of water, and because there are 60 seconds in a minute). In order to convert W/m^2, latent heat of evaporation of water was presumed to be 2260 kJ/kg [47]. Therefore, the TER in W/m^2 was divided by 2.26 x 10^7 to obtain the value in x 10^{-7} g/cm^2/sec.

As many of the manuscripts were published prior to the 2007 DEWS [61] the 2011 International Workshop on MGD [62] and the 2017 TFOS DEWS II [2] definition and classification reports, the type of dry eye has been reclassified based on the current standards.

TER values that were conducted on samples that included both normal eyes and dry eyes have not been included in the updated summary. Measurements recorded with contact lenses or on participants that had been wearing contact lenses have also been excluded. The effect of different treatments for dry eye and MGD, such as eye drops or warm compresses, were also excluded.

Results:

Table 1 provides an updated summary table of TERs for normal and dry eyes. This includes all four of the animal studies and 12 out of 14 of the human studies that Mathers cited [55], in addition

to more recent studies conducted between 2003 to 2016. The revised summary of TER has been expressed as the mean ± standard deviation, with one exception, as the TER was reported as the mean ± standard error [63]. All TERs have been stated in units of x 10^{-7} g/cm^2/sec, except for the relatively few values expressed in units of x 10^{-7} g/sec [7], x 10^{-7} g/sec/eye [63] and W/min [49].

The table reveals that the wide range of TERs for normal and dry eyes agrees with that previously reported in the literature. The TERs for early studies conducted on rabbit eyes ranges from 7.8 to 41.7 x 10^{-7} g/cm^2/sec, and between 0.02 to 29 x 10^{-7} g/cm^2/sec for normal, human eyes. It should be noted that the 0.02 g/cm^2/sec measurement was recorded in a room with an average temperature of 23.1°C and an average ambient RH of 47.1% [37]; however, this value was obtained after correcting the raw data to an arbitrary ambient temperature of 25°C and RH of 50% in order to enhance the sensitivity of the technique [3]. The higher TER of 29 x 10^{-7} g/cm^2/sec measurement was recorded at a drier ambient RH of 20% [12]. If the ambient RH range is then narrowed to exclude TERs recorded below 40% RH, the highest normal TER is 26.9 g/cm^2/sec, which was found using the repeatability of measurements taken with a thermal camera [48]. The range of TERs for humans diagnosed with different types of dry eye and/or MGD was even more variable, with the values ranging from 0.41 to 59.1 x 10^{-7} g/cm^2/sec.

The TER reported by Tomlinson in 1991 was removed from this summary because evaporation rates were not explicitly stated in either the Tomlinson and Trees [27] or Tomlinson and colleagues [28] papers that were cited by Mathers [55]. There was also only one reference to a study conducted by Shimazaki [63] cited by Mathers. As the literature search was unable to find any other studies published by Shimazaki and colleagues in 1995 on the topic of evaporation, the second reference

to a study by Shimazaki in 1995 has been considered as a duplicate value and has not been included in the tables.

These results also assume that there was a typographical error in reporting units of TER in one paper [41], as there was a discrepancy in the units reported between the table ($g/m^2/s$) and the figures ($g/m^2/hr$). The reported mean value of 49.91 $g/m^2/s$ would be equivalent to 4.991 x 10^{-3} $g/cm^2/sec$, which is much larger than any of the other reported TERs in the table. Therefore, it seems appropriate to assume that the correct units should be $g/m^2/hr$, as the ServoMed evaporimeter expresses TER in these units [64].

To aid in interpretation, an additional table (Table 2) has been included that summarises the reported TERs categorised by the type of instrument that was used. This will hopefully aid in recognising any trends within and between different research groups. It appears that the same group of normal subjects may have been used in two different manuscripts [20, 22]. The same TER also appears for evaporative dry eye in two papers [38, 39] with different sample sizes.

Discussion:

In view of the increased number of studies published since the Mathers paper, and the increasing importance of TER measurement as reported by the TFOS DEWS reports, it was important to produce an updated version of the published values of evaporation rate. Moreover, researchers have reported using the data presented in the literature review by Mathers [55] as a reference with which to compare their results [12, 65]. Researchers who have used the summarised data from the

literature review by Mathers [55] as a reference may find that their conclusions would have been different if the originally reported values had been used.

Whilst compiling this revised summary of TER for normal and dry eyes, various problems were encountered, including inconsistiencies with the reported rates of evaporation, problems with the reported relative humidity, and difficulties in converting the TER into a single unit of x 10^{-7} g/cm^2/sec. Each of these problems will be discussed in further detail below.

Issues with the reported rate of tear evaporation

Some puzzling values were encountered when searching for the first measurements conducted on humans in 1980. A paper [66] in 1980, which described an evaporimeter in Japanese, was subsequently followed by a paper [67] in English in the following year. Both abstracts contained the same evaporation rates, described the same test subjects, and use of a modified ServoMed EP1 evaporimeter to measure TER. The text in the Japanese paper reported the rate of evaporation in normal eyes as 87 g/m^2/hr and 26.9 x 10^{-7} g/cm^2/sec. However, by using the calculation described in the methods section for unit conversion, if the rate in g/m^2/hr is divided by 3.6, the equivalent TER would be 24.2 x 10^{-7} g/cm^2/sec. It seems sensible to assume that the original value for TER in normal eyes should be considered as 87 g/m^2/hr, because the English language paper states that the evaporimetry rate was expressed in g/m^2/hr, and the instrument also reports TER in these units. It seems likely that there was an error in the original paper [66] in converting the values from g/m^2/hr to x 10^{-7} g/cm^2/sec. The rate of evaporation for normal eyes therefore used was 24.2 x 10^{-7} g/cm^2/sec (based on an original rate of 87 g/m^2/hr).

Mathers' summary of published evaporation rates reported that Yamada and Tsubota [68] found the highest TER in normal subjects to be 32.4 x 10^{-7} g/cm^2/sec, with a lower TER of 16.5 x 10^{-7} g/cm^2/sec for dry eyes. However, it is important to note that the values reported in the original paper [68], as 32.4 and 16.5, correspond to an evaporation coefficient, K, that was recorded in a different unit of x 10^{-4}/sec. The correct values of evaporation rate are therefore much smaller, at 8.3 x 10^{-7} g/cm^2/sec for normal eyes and 4.6 x 10^{-7} g/cm^2/sec for dry eyes [68]. Correcting the normal TER to its originally published value finds that it falls within the range of other published human TERs conducted between 1980 and 2003.

Issues with the reported rate of relative humidity

Discrepancies were also noted in reporting the RH values for rabbits and humans between the Japanese [69] and English [67] versions of the Yamada and Tsubota papers. The Japanese paper reported 42% RH for the rabbit, while the English paper reported 60%. For humans, the Japanese paper also reported 42% RH for testing normal and dry eyes; however, the English paper reported 40% RH for normal eyes and 42% RH for dry eyes. All of these RH values have been added to the updated tables.

Reporting the incorrect level of RH can cause potential problems, because TER has been shown to increase as RH decreases [17, 18, 20-22, 25, 33, 43]. If an attempt was made to replicate a study, and this attempt mistakenly used a RH of 60% when the RH had been 42%, then the results would likely end up significantly different due to the effect that humidity would have on the results.

Issues with converting values to a single unit of measurement

Many different units of measurement have been used to express the TER. This can lead to difficulty comparing and interpreting the reported TER between different studies, as there is even a lack of consistency in using the same unit within an instrument [47, 49] or ones based on the same design [8, 22, 25].

Analysis of the original manuscripts found that TER was most often reported in units of x 10^{-7} $g/cm^2/sec$ and $g/m^2/hr$. However, some researchers used units of x 10^{-6} $g/cm^2/sec$ [12], $g/mm^2/hr$ [70], $mg/cm^2/hr$ [71], x 10^{-7} g/sec [7], x 10^{-7} g/sec/eye [63], $\mu l/cm^2/min$ [16-23], W/m^2 [47, 48] and W/min [49]. The values expressed in units of x 10^{-7} g/sec [7] or x 10^{-7} g/sec/eye [63] were not converted because Tsubota and Yamada [7] stated that they did not try to calculate the TER in relation to the exposed ocular surface area. No attempt was made in this summary to convert these values because it was not possible to decide on a suitable mean value for the exposed ocular surface area. A wide range of mean values for exposed ocular surface area, varying from 1.13 cm^2 [72] to 2.4 cm^2 [52], have been previously reported in the literature. Similarly, the conjunctival TER of 66.1 W/min, reported by Yeo and colleagues [49] was not converted, as the size of the conjunctival surface that was measured was unknown.

Additional problems were encountered when trying to compile this summary because some researchers used multiple values to express TER within the same manuscript. Goto and colleagues [6] reported the TER using two different methods. One rate was calculated based on the area within the eye cup and the other one corrected for the exposed ocular surface area using the calculation created by Rolando and Refojo [5]. This calculation ($y = 0.28x - 0.44$, $r = 0.991$) allows the exposed ocular surface of the eye to be estimated from a measurement of the palpebral aperture

size. As other studies reported in this summary have used the Rolando and Refojo calculation [5, 8, 13, 15, 53], or photographed the eye [3, 16-20, 22, 36, 37] to estimate the exposed surface area of the eye, Tables 1 and 2 report the TER calculation for Goto and colleagues [6] based on the exposed ocular surface area rather than the area of the eye cup.

Liu and colleagues [73] also calculated the TER using two different methods. One method used the difference between the open eye and the closed eye, to account for the evaporation from the ocular surface, and found 4.6 ± 3.0 x 10^{-7} g/cm^2/sec for normal eyes. The authors created a new equation to calculate the exact evaporation rate of the ocular surface and found the TER to be significantly larger at 39.3 ± 13.6 x 10^{-7} g/cm^2/sec. The updated values of TER report the former rather than the latter value to maintain consistency with the previous researcher, who used an evaporimeter [6] containing the same humidity sensor.

A review of the literature has also shown that the values of 32.4 x 10^{-7} g/cm^2/sec and 16.5 x 10^{-7} g/cm^2/s, which should have been in units of x 10^{-4}/sec [68], appear in a meta-analysis [58] which determined cut-off values of TER for normal versus dry eye. The values that were included in the meta-analysis were approximately four times larger than the originally reported TER. Values originally reported in x 10^{-7} g/sec [7] also appear in the meta-analysis as units of 10^{-7} g/sec/cm^2. When Tsubota and Nakamori [74] published work which reported the TER at 40% humidity (TEROS 40) in two different units, they found the mean was 17.6 ± 6.6 x 10^{-7}g/sec/eye and 7.8 ± 2.2 x 10^{-7}g/sec/cm^2. Based on this estimate, the value used in the meta-analysis will also be approximately two times larger than those that were corrected for the exposed ocular surface of the eye. Therefore, there may have been an over-estimation in calculating the mean rate of

evaporation in normal and dry eyes in the meta-analysis. This summary has not attempted to re-work the meta-analysis with this new information; however, these revised values should hopefully serve as a new reference for future work in this field.

Problems in converting units of measurement has also led to mistakes in previously published work, with Tomlinson and colleagues [58] noting that Tomlinson's earlier work with Cedarstaff [4], using resistance hygrometry, over-estimated the TER by 100x. In order to prevent future mistakes in calculating TER and to aid in the interpretation of data, it would be useful if all evaporation rates could be expressed in a single unit, such as x 10^{-7} g/cm^2/sec.

Although King-Smith has suggested expressing the evaporation rate in units of μm/min [60], this paper proposes that x 10^{-7} g/cm^2/sec is the most appropriate unit, since it reflects the small surface area of the exposed eye (cm^2) and the short time frames involved in the measurement (s). When an evaporimeter is used, the size of the exposed ocular surface should either be estimated from the size of the palpebral aperture, using the Rolando and Refojo formula [5], or by determining the size of the exposed ocular surface from a photograph.

Tear evaporation rate and the type of dry eye

The updated summary of TER shows that some investigators found increased TER in subjects with dry eye, ADDE, EDE or MGD, while others did not. One study [7] that found lower rates of evaporation in subjects with dry eyes hypothesised that this may due be differences in the relative amount of tear evaporation between normal and dry eyes. Tear dynamics depend on three components: tear production, tear evaporation and tear drainage. In dry eyes, tear dynamics occur

at low levels in all three categories; however, tear evaporation has a larger relative contribution to tear dynamics in dry eyes than normal eyes due to the decreased tear volume. Another study [38] that found increased TERs in subjects with ADDE, attributed this to an irregular, thick lipid layer that leads to increased evaporation. It has also been suggested that when normal TERs were found in people with MGD, it may be because they only had symptomatic MGD or MGD-associated ocular surface disease [75] and had not yet progressed enough to alter the lipid layer of the tear film and result in EDE. It has been suggested to think of dry eye as occurring along a continuum, with ADDE on one end and EDDE on the other [38] and this is supported by the new TFOS DEWS II classification of dry eye [2]. This could contribute to the variability in TERs with people with a mixed aetiology of dry eye. For some people, ADDE will play a larger role, while the opposite will hold true for others, even though their reported symptoms may be similar. For those towards the EDE end of the spectrum, it would be expected that these TERs would be higher than those further towards the ADDE end.

Conclusions:

Two new tables have been created to provide an accurate representation of the TER for normal and diseased or dry eyes. The values in the table are based on the original values reported by the author and have been converted to units of x 10^{-7} g/cm^2/sec (where possible). The authors cited by Mathers [55] in his literature review have been used to represent studies conducted between 1941 and 2002. Newer data has also been added for studies carried out between 2003 and 2016. These tables can be used as a reference for other researchers to compare their results.

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Table 1: Summary of published TERs for normal and dry eye

Year	Investigator	Animal	Normal Evaporation Rate ($\times 10^{-7}$ g/cm^2/sec)	RH(%)	Dry Eye Evaporation Rate ($\times 10^{-7}$ g/cm^2/sec)	Classification	Description
1941	von Bahr[70]	Rabbit	*41.7 ± NR*				
1961	Mishima[71]	Rabbit	7.8 ± NR				
1969	Iwata[76]	Rabbit	10.1 ± NR				
1980	Hamano[66, 67]	Rabbit	11.4[66, 67] ± 4.4[67]	42[66]/ 60[67]			
1980	Hamano[66, 67]	Human	*24.2[66, 67][a] ± 5.8[67]*	40[67] - 42[66, 67]	*13.6 ± 3.1[66, 67]*	DE	
1983	Rolando[5, 77]	Human	4.07 ± 0.40[5, 77]	29.5	8.03 ± 2.83[77]	ADDE	
				29.5	8.17 ± 2.65[5]		TF abnormalities
1990	Yamada[68]	Human	*8.3 ± 1.9*	40	*4.6 ± 2.9*	ADDE	
1992	Tsubota[7]	Human	15.6 ± 3.8[b]	40	9.5 ± 5.6[b]	DE	
1993	Mathers[8]	Human	14.7 ± 6.4	30	47.6 ± 20.1	ADDE	
			12.1 ± 5.5	40	33.0 ± 12.4	ADDE	
1993	Mathers[15]	Human	14.8 ± 6	30	49.9 ± 21	EDE (MGD)	Dropout
				30	59.1 ± 28	Mixed	Dropout
1995	Shimazaki[63]	Human	*13.09 ± 1.35[c,d]*	40	*10.41 ± 1.28[c,d]*	EDE (MGD)	Obs
				40	18.39 ± 1.43[c,d]	EDE (MGD)	Dropout
				40	14.43 ± 1.87[c,d]	EDE (MGD)	Obs and dropout
1996	Mathers[13]	Human	13 ± 6	30	25 ± 35	DE	ADDE or hyperosm
1996	Mathers[53]	Human	15.1 ± 8.62	NR	23.9 ± 17.47	ADDE	
				NR	22.81 ± 16.33	EDE (MGD)	Mean of all MGD types
				NR	27.67 ± 18.25	Mixed	Obs
				NR	12.32 ± 8.76	Mixed	Seb
				NR	16.06 ± 8.92	Mixed	Rosacea
				NR	20.05 ± 11.32	Mixed	Seb and obs
1997	Craig[3]	Human	0.39 ± NR	50	1.6 ± NR	EDE	No visible lipid layer/abnormal coloured fringes
				50			
2000	Craig[37]	Human	0.02 ± 0.14	50	0.41 ± 0.19	DE	7 out of 8 patients had a lipid-deficient tear film
				50			
2003	Goto[6]	Human	*5.7 ± 1.4[e]*	10-15	*7.4 ± 2.8[e]*	EDE (MGD)	Obs

Year	Author	Species	Value	Age	Value	Classification	Condition
2003	McCulley[23]	Human	10.92 ± 4.28	NR	11.67 ± 6.13	ADDE	
				NR	10.55 ± 7.08	Mixed	Turbid/difficult-to-express secretions
2004	Matsumoto[78]	Human		NR	6.98 ± NR		Ectrodactyly-ectodermal dysplasia-clefting syndromes
2005	Liu[73]	Human	4.6 ± 3.0[f]	NR	7.4 ± 3.2[f]		Floppy eyelid syndrome
2006	McCulley[22]	Human	10.8 ± 3.7	20-25	11.2 ± 5.2	ADDE	
			6.2 ± 2.7	40-45	6.2 ± 3.7	ADDE	
				20-25	11.3 ± 8.8	Mixed	Turbid/difficult-to-express secretions
				40-45	5.3 ± 3.0	Mixed	Turbid/difficult-to-express secretions
2006	McCulley[21]	Human	9.7 ± 3.0[g]	25-35	8.0 ± 2.8[g]	DE	
			7.2 ± 2.7[g]	35-45	6.2 ± 1.8[g]	DE	
			7.8 ± 3.7[h]	25-35	7.3 ± 2.2[h]	DE	
			4.8 ± 1.5[h]	35-45	5.7 ± 1.5[h]	DE	
2007	Uchiyama[20]	Human	10.8 ± 3.7	20-25	11.0 ± 5.0	ADDE	
			6.2 ± 2.7	40-45	6.0 ± 3.7	ADDE	
				20-25	9.5 ± 5.0	Mixed	Turbid/difficult-to-express secretions
				40-45	5.2 ± 3.2	Mixed	Turbid/difficult-to-express secretions
2007	Goto[79]	Human		10-15	5.9 ± 3.5	ADDE	SS
				10-15	2.9 ± 1.8	ADDE	Non-SS dry eye
2008	Matsumoto[80]	Human	2.5 ± 0.9	50-60			Non-smokers
			7.7 ± 0.2	50-60			Smokers
2008	Matsumoto[81]	Human	4.30 ± 3.82	30-50	6.37 ± 3.72	EDE (MGD)	
2008	Guillon[25]	Human	15.1 ± 7.3	30			
			11.3 ± 6.8	40			
2008	Uchiyama[19]	Human		25-35	14.3 ± 6.2	ADDE	
				35-45	10.4 ± 5.2	ADDE	
				25-35	14.6 ± 6.4	ADDE	
				35-45	10.5 ± 5.5	ADDE	
2009	Wojtowicz[18]	Human	11.5 ± 4.0	25-35			
			8.2 ± 3.0	35-45			
2009	McCann[36]	Human	5.0 ± 3.0	NR	12.9 ± 6.4		Blepharitis
2009	Khanal[38]	Human	5.8 ± 2.8	NR	9.6 ± 5.6	ADDE	SS, GVHD, RA
				NR	12.8 ± 10.5	EDE	Posterior blepharitis, partial blink, visual display related, lipid abnormalities
2010	Wang[82]	Human	2.2 ± 1.53	10-15	3.6 ± 1.66	ADDE, Mixed	GVHD mild DE, GVHD mild DE + obs

Year	Author	Species				Type	Notes
				10-15	5.98 ± 3.61	ADDE, Mixed	GVHD severe DE, GVHD severe DE + obs
2010	Wojtowicz[17]	Human		25-35	8.2 ± 3.8	ADDE	
				35-45	5.3 ± 2.7	ADDE	
				25-35	7.8 ± 3.2	ADDE	
				35-45	5.2 ± 2.3	ADDE	
2010	Guillon[24]	Human	16.6 ± NR	30			
			13.7 ± NR	40			
2010	Tan[47]	Human	25.38 ± 5.63	70 ± 4			
2011	Arciniega[16]	Human	5.5 ± 2.0	25-35	9.3 ± 2.7	ADDE	
			3.8 ± 1.3	35-45	6.7 ± 1.3	ADDE	
				25-35	9.2 ± 4.3	Mixed	Turbid/difficult-to-express secretions
				35-45	6.2 ± 3.2	Mixed	Turbid/difficult-to-express secretions
2012	Khanal[39]	Human		NR	13.3 ± 5.1	ADDE	GVHD
				NR	7.0 ± 4.4	ADDE	SS
				NR	12.8 ± 10.5	EDE (MGD)	
2012	Ibrahim[83]	Human	3.3 ± 5.5	30-50	9.8 ± 5.0		Atopic-keratoconjunctivitis
				30-50	7.4 ± 2.7	EDE (MGD)	Obs
2013	Tomlinson[41]	Human	4.7 ± 2.4[i]	20	13.9 ± 6.7[i]	ADDE	
			4.4 ± 2.1[i]	20	14.0 ± 5.5[i]	ADDE	
			4.2 ± 1.8[i]	20	15.3 ± 6.2[i]	ADDE	
2013	Madden[33]	Human	21.6 ± 4.0	5	28.1 ± 3.1	ADDE	
			6.6 ± 1.2	40	16.6 ± 2.9	ADDE	
			0.3 ± 1.8	70	0.3 ± 2.4	ADDE	
2013	Abusharha[43]	Human	28.2 ± NR	5			
			12.8 ± NR	40			
2013	Petznick[48]	Human	26.9 ± 2.4	61 – 67			
			13.5 ± NR	45 at 30°C			
			11.8 ± NR	65 at 30°C			
2014	Peng[12]	Human	29 ± NR	20			
			22 ± NR	40			
2016	Alghamdi[50]	Human	21.9 ± 9.2	45.5 ± 9			
2016	Yeo[49]	Human		NR	66.1 ± 21.1[j]	EDE, Mixed	MG pouting and visible plug above lid margin
2016	Abusharha[42]	Human	5.6 ± NR	40 at 5°C			
			17.4 ± NR	40 at 25°C			
2016	Jeon[11]	Human	15.2 ± 3.9	41, 40.2	17.8 ± 3.0	ADDE	
				40.2	17.0 ± 4.1	EDE	

All evaporation rates are expressed as the mean ± standard deviation in units of x 10^{-7} g/cm^2/sec, except where denoted by [b,c,d,j]. Italicised values indicate different mean evaporation rates than the ones reported by Mathers [55] in 2004.

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RH: relative humidity, DE: dry eye, TF: tear film, Hyperosm: hyperosmolarity, ADDE: aqueous deficient dry eye, EDE: evaporative deficient dry eye, Mixed: aqueous deficient and evaporative deficient dry eye, Dropout: meibomian gland drop out, Obs: obstructive meibomian gland dysfunction, MGD: meibomian gland dysfunction, Seb: seborrheic meibomian gland dysfunction, NR: not reported, SS: Sjögren's syndrome, RA: rheumatoid arthritis, GVHD: graft-versus-host disease, MG: meibomian gland.

[a] Calculated based on an evaporation rate of 87 ± 21 g/m^2/hr

[b] Units = x 10^{-7} g/sec

[c] Units = x 10^{-7} g/sec/eye

[d] Reported as mean ± standard error

[e] Evaporation rate calculated based on the exposed area of ocular surface

[f] Evaporation rate was also reported as normal = 39.3 ± 13.6 x 10^{-7} g/cm^2/sec and floppy eyelid syndrome = 73.1 ± 29.7 x 10^{-7} g/cm^2/sec

[g] Female

[h] Male

[i] Evaporation rate calculated based on the assumption that the original units were g/m^2/hr (not g/m^2/s)

[j] Conjunctival evaporation rate, units = W/min

Table 2: Summary of human TERs for normal and dry eyes categorised by type of evaporimeter

Evaporimeter/ Instrument	Investigator (Year)	Normal Evaporation Rate ($x10^{-7}$ g/cm²/sec)	RH(%)	Dry Eye Evaporation Rate (x 10^{-7} g/cm²/sec)	Dry Eye Type	Description
ServoMed EP1 (contact)	Hamano[67] (1980)	24.2[66, 67][a] ± 5.8[67]	40[67] - 42[66, 67]	13.6 ± 3.1[66, 67]		
Rolando-Refojo tear	Rolando[5, 77] (1983)	4.07 ± 0.40[5, 77]	29.5	8.03 ± 2.83[77]	ADDE	
			29.5	8.17 ± 2.65[5]		TF abnormalities
Closed-chamber, unventilated	Yamada[68] (1990)	8.3 ± 1.9	40	4.6 ± 2.9	ADDE	
	Tsubota[7] (1992)	15.6 ± 3.8[b]	40	9.5 ± 5.6[b]	DE	
	Shimazaki[63] (1995)	13.09 ± 1.35[c,d]	40	10.41 ± 1.28[c,d]	EDE (MGD)	Obs
			40	18.39 ± 1.43[c,d]	EDE (MGD)	Dropout
			40	14.43 ± 1.87[c,d]	EDE (MGD)	Obs and dropout
Closed-chamber, ventilated	Mathers[8] (1993)	14.7 ± 6.4	30	47.6 ± 20.1	ADDE	
		12.1 ± 5.5	40	33.0 ± 12.4	ADDE	
	Mathers[15] (1993)	14.8 ± 6	30	49.9 ± 21	EDE (MGD)	Dropout
			30	59.1 ± 28	Mixed	Dropout
	Mathers[13] (1996)	13 ± 6	30	25 ± 35	DE	ADDE or hyperosm
	Mathers[53] (1996)	15.1 ± 8.62	NR	23.9 ± 17.47	ADDE	
			NR	22.81 ± 16.33	EDE (MGD)	Mean of all MGD types
			NR	27.67 ± 18.25	Mixed	Obs
			NR	12.32 ± 8.76	Mixed	Seb
			NR	16.06 ± 8.92	Mixed	Rosacea
			NR	20.05 ± 11.32	Mixed	Seb and obs
Closed-chamber, ventilated based on Mathers	McCulley[23] (2003)	10.92 ± 4.28	NR	11.67 ± 6.13	ADDE	
			NR	10.55 ± 7.08	Mixed	Turbid/difficult-to-express
	McCulley[22] (2006)	10.8 ± 3.7	20-25	11.2 ± 5.2	ADDE	
		6.2 ± 2.7	40-45	6.2 ± 3.7	ADDE	
			20-25	11.3 ± 8.8	Mixed	Turbid/difficult-to-express
			40-45	5.3 ± 3.0	Mixed	Turbid/difficult-to-express
	McCulley[21] (2006)	9.7 ± 3.0[e]	25-35	8.0 ± 2.8[e]	DE	
		7.2 ± 2.7[e]	35-45	6.2 ± 1.8[e]	DE	
		7.8 ± 3.7[f]	25-35	7.3 ± 2.2[f]	DE	
		4.8 ± 1.5[f]	35-45	5.7 ± 1.5[f]	DE	

	Uchiyama[20] (2007)	10.8 ± 3.7 6.2 ± 2.7	20-25 40-45 20-25 40-45	11.0 ± 5.0 6.0 ± 3.7 9.5 ± 5.0 5.2 ± 3.2	ADDE ADDE Mixed Mixed	Turbid/difficult-to-express Turbid/difficult-to-express
	Uchiyama[19] (2008)		25-35 35-45 25-35 35-45	14.3 ± 6.2 10.4 ± 5.2 14.6 ± 6.4 10.5 ± 5.5	ADDE ADDE ADDE ADDE	
	Wojtowicz[18] (2009)	11.5 ± 4.0 8.2 ± 3.0	25-35 35-45			
	Wojtowicz[17] (2010)		25-35 35-45 25-35 35-45	8.2 ± 3.8 5.3 ± 2.7 7.8 ± 3.2 5.2 ± 2.3	ADDE ADDE ADDE ADDE	
	Arciniega[16] (2011)	5.5 ± 2.0 3.8 ± 1.3	25-35 35-45 25-35 35-45	9.3 ± 2.7 6.7 ± 1.3 9.2 ± 4.3 6.2 ± 3.2	ADDE ADDE Mixed Mixed	Turbid/difficult-to-express Turbid/difficult-to-express
Closed-chamber, ventilated based on Mathers	Guillon[25] (2008) Guillon[24] (2010)	15.1 ± 7.3 11.3 ± 6.8 16.6 ± NR 13.7 ± NR	30 40 30 40			
ServoMed (EP1 or EP3) (non-contact)	Craig[3] (1997)	0.39 ± NR	50	1.6 ± NR	EDE	No visible lipid layer/abnormal coloured fringes
	Craig[37] (2000)	0.02 ± 0.14	50	0.41 ± 0.19	DE	7 out of 8 patients had a lipid-deficient tear film
	McCann[36] (2009)	5.0 ± 3.0	NR	12.9 ± 6.4		Blepharitis
	Khanal[38] (2009)	5.8 ± 2.8	NR NR	9.6 ± 5.6 12.8 ± 10.5	ADDE EDE	SS, GVHD, RA Posterior blepharitis, partial blink, visual display related, lipid abnormalities
	Khanal[39] (2012)		NR NR NR	13.3 ± 5.1 7.0 ± 4.4 12.8 ± 10.5	ADDE ADDE EDE (MGD)	GVHD SS
	Tomlinson[41] (2013)	4.7 ± 2.4[g] 4.4 ± 2.1[g] 4.2 ± 1.8[g]	20 20 20	13.9 ± 6.7[g] 14.0 ± 5.5[g] 15.3 ± 6.2[g]	ADDE ADDE ADDE	
	Madden[33] (2013)	21.6 ± 4.0 6.6 ± 1.2	5 40	28.1 ± 3.1 16.6 ± 2.9	ADDE ADDE	

		0.3 ± 1.8	70	0.3 ± 2.4	ADDE	
	Abusharha[43] (2013)	28.2 ± NR	5			
		12.8 ± NR	40			
	Abusharha[42] (2016)	5.6 ± NR	40 at 5°C			
		17.4 ± NR	40 at 25°C			
Ventilated, quartz crystal microbalance	Goto[6] (2003)	5.7 ± 1.4h	10-15	7.4 ± 2.8h	EDE (MGD)	Obs
	Matsumoto[78] (2004)		NR	6.98 ± NR		Ectrodactyly-ectodermal dysplasia-clefting syndromes
	Liu[73] (2005)	4.6 ± 3.0i	NR	7.4 ± 3.2i		Floppy eyelid syndrome
	Goto[79] (2007)		10-15	5.9 ± 3.5	ADDE	SS
			10-15	2.9 ± 1.8	ADDE	Non-SS dry eye
	Matsumoto[80] (2008)	2.5 ± 0.9	50-60			Non-smokers
		7.7 ± 0.2	50-60			Smokers
	Matsumoto[81] (2008)	4.30 ± 3.82	30-50	6.37 ± 3.72	EDE (MGD)	
	Wang[82] (2010)	2.2 ± 1.53	10-15	3.6 ± 1.66	ADDE, Mixed	GVHD mild DE, GVHD mild DE + obs
			10-15	5.98 ± 3.61	ADDE, Mixed	GVHD severe DE, GVHD severe DE + obs
	Ibrahim[83] (2012)	3.3 ± 5.5	30-50	9.8 ± 5.0		Atopic-keratoconjunctivitis
			30-50	7.4 ± 2.7	EDE (MGD)	Obs
VarioTHERM head II thermal camera	Tan[47] (2010)	25.38 ± 5.63	70 ± 4			
	Petznick[48] (2013)	26.9 ± 2.4	61 – 67			
		13.5 ± NR	45 at 30ºC			
		11.8 ± NR	65 at 30ºC			
	Yeo[49] (2016)		NR	66.1 ± 21.1j	EDE, Mixed	MG pouting and visible plug above lid margin
Berkeley Flow	Peng[12] (2014)	29 ± NR	20			
		22 ± NR	40			
VapoMeter	Alghamdi[50] (2016)	21.9 ± 9.2	45.5 ± 9			
Tewameter TM300	Jeon[11] (2016)	15.2 ± 3.9	41, 40.2	17.8 ± 3.0	ADDE	
			40.2	17.0 ± 4.1	EDE	

All evaporation rates are expressed as the mean ± standard deviation in units of x 10^{-7} g/cm^2/sec, except where denoted by [b,c,d,j].

RH: relative humidity, TF: tear film, ADDE: aqueous deficient dry eye, DE: dry eye, MGD: meibomian gland dysfunction, EDE: evaporative deficient dry eye, Mixed: aqueous deficient and evaporative deficient dry eye, Obs: obstructive meibomian gland dysfunction, Hyperosm: hyperosmolarity, Dropout: meibomian gland

drop out, Hyperosm: hyperosmolarity, Seb: seborrheic meibomian gland dysfunction, NR: not reported, SS: Sjögren's syndrome, GVHD: graft-versus-host disease, RA: rheumatoid arthritis, MG: meibomian gland.

[a] Calculated based on an evaporation rate of 87 ± 21 g/m^2/hr

[b] Units = x 10^{-7} g/sec

[c] Units = x 10^{-7} g/sec/eye

[d] Reported as mean ± standard error

[e] Female

[f] Male

[g] Evaporation rate calculated based on the assumption that the original units were g/m^2/hr (not g/m^2/s)

[h] Evaporation rate calculated based on the exposed area of ocular surface

[i] Evaporation rate was also reported as normal = 39.3 ± 13.6 x 10^{-7} g/cm^2/sec and floppy eyelid syndrome = 73.1 ± 29.7 x 10^{-7} g/cm^2/sec

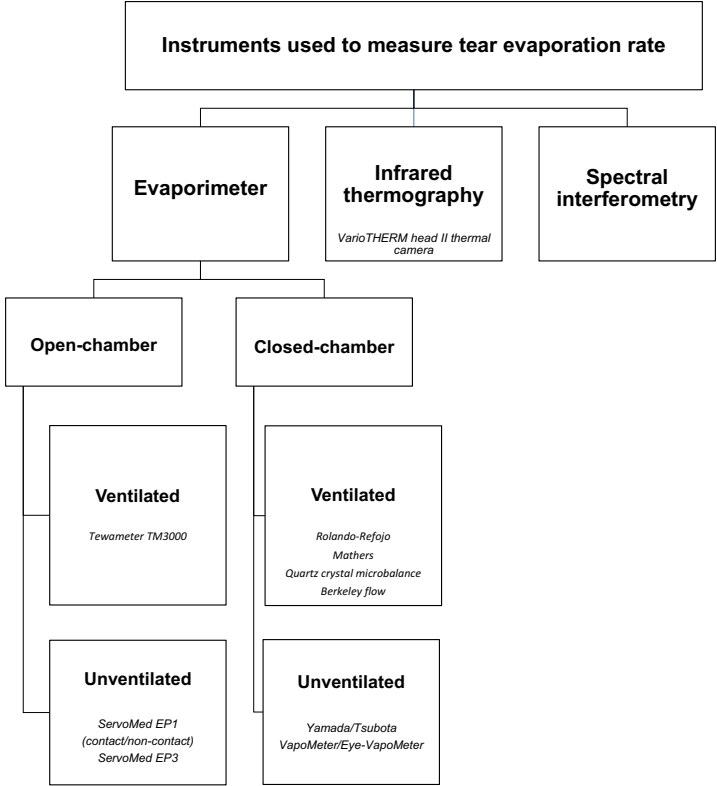[j] Conjunctival evaporation rate, units = W/min

Figures

Figure 1: Schematic diagram of the types of instruments that have been used to measure evaporimetry.
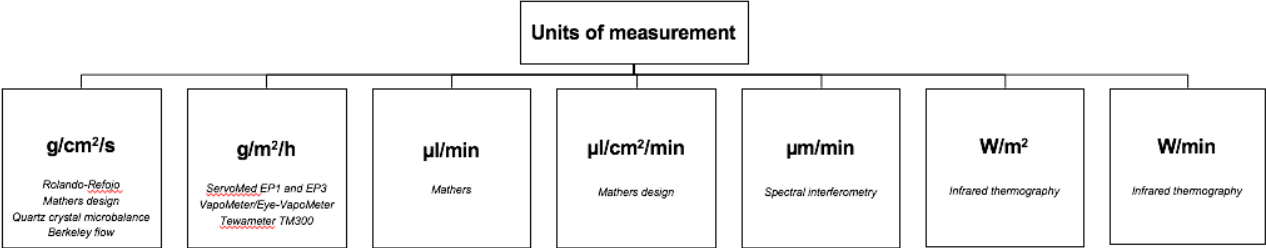

Figure 2: Diagram of different units of measurement and the type of instrument that have been used to report tear evaporation rates.