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DIELECTRIC PARAMETERS OF DYED COTTON FABRICS

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ABSTRACT

Non-contact electrodes have capacities in long-term monitoring of electrocardiogram (ECG) and early detection of heart abnormalities. In non-contact ECG sensing, the dielectric materials strongly influence the effectiveness of the electrodes. Over the past three decades, there has been extensive research on fabric dielectrics because they are harmless, plentiful, comfortable, and skin conformable. A high and stable permittivity is essential in fabric dielectrics used in non-contact electrodes. However, the dye used on fabrics can immensely influence their relative permittivity and electrode coupling capacitance. This study investigates the effects of dye on dielectric parameters of cotton fabrics using the parallel plate technique in dry and moisturized conditions. The results show that undyed fabric has higher capacitance but lower relative permittivity in dry and moisturized conditions. In contrast, dyed fabrics showed higher permittivity, but slight differences were found depending on the dye used. These findings demonstrate that dyed fabrics are more effective as dielectrics for capacitive ECG electrodes.

Keywords: Capacitive ECG electrode, dye, fabric dielectrics, capacitance, relative permittivity.

INTRODUCTION

For more than half a century, capacitive biopotential electrodes have been studied for long-term measurement of biopotential signals such as the electrocardiogram (ECG) (Lopez & Richardson, 1969), electroencephalogram (EEG) (Matsuo, Iinuma, & Esashi, 1973), electromyogram (EMG) (Potter & Menke, 1970), and other physiological activities. Long-term ECG monitoring can offer both physicians and patients the benefits of early cardiac abnormality detection and avoid missing critical symptoms. In health care settings, the wet electrodes are the conventional diagnostic devices used to acquire ECG signals. However, wet ECG requires skin abrasion and conductive paste to minimize skin impedance. Thus, it achieves high-quality ECG signals. Furthermore, since the conductive paste is volatile and causes skin allergies, wet electrodes are considered unsuitable for long-term ECG measurement.

Alternative to wet electrodes is dry contact electrodes. They do not require conductive paste and skin abrasion. Several studies have been published exploring the capabilities of dry contact electrodes for long-term ECG measurement (Anusha, Preejith, Akl, Joseph, & Sivaprakasam, 2018; Chlaihawi, Narakathu, Emamian, Bazuin, & Atashbar, 2018; Choi et al., 2019; Li et al., 2019; Xu, Liu, He, & Yang, 2019). The drawbacks of dry electrodes are high skin impedance (Gandhi, Khe, Chung, Chi, & Cauwenberghs, 2011), artifact noise, powerline interference (Searle & Kirkup, 2000), and the influence of skin exudates (Ueno et al., 2007). Capacitive electrodes are designed to sense ECG signals in non-contact mode via a dielectric material. Dielectrics make capacitive ECG electrodes convenient and comfortable for users. However, the materials employed as dielectrics remain a constraint to attain efficient ECG measurement.

Dielectrics are materials with low electrical conductivity and get polarised when exposed to an electric field (Grimnes & Martinsen, 2015). Past dielectrics incorporated into capacitive ECG electrodes were metal-oxides such as aluminum-oxide (Lopez & Richardson, 1969), silicon-oxide(Ko, Neuman, Wolfson, & Yon, 1970), tantalum-oxide (Lagow, Sladek, & Richardson, 1971), and barium titanate (Matsuo et al., 1973). Metal-oxide dielectrics can achieve a high dielectric constant. Despite this advantage, they are rigid, show poor skin conformity, and require shielding, bio-amplifiers with high input impedance, and hazardous fabrication procedures.

Many studies have explored fabric dielectrics for capacitive ECG measurement (Chen, Chang, & Xie, 2017; Lim, Kim, & Park, 2007; Ng & Reaz, 2017; Ng, Reaz, Crespo, Cicuttin, & Chowdhury, 2020; Steffen, Aleksandrowicz, & Leonhardt, 2007; Ueno et al., 2007). Fabrics offer several dielectric advantages over metal-oxide despite their low dielectric constant. They are widely available, soft, skin conformable, and pose no health risk. In long-term biopotential sensing, a stable relative permittivity and coupling capacitance are essential. However, the dyes or colorants used to colour fabrics highly affect the dielectric parameters of fabrics. In this study, we investigate the effect of dye on capacitance and relative permittivity of cotton fabric dielectrics. The paper is organized as follows: Section I introduces biopotential electrodes and dielectrics. Section II describes the materials and experimental techniques employed. In Section III, the results are given and discussed, while Section IV presents the conclusion drawn.

MATERIALS AND METHODS

Chemicals and Raw Materials

Undyed (white) cotton fabrics and colorants (in powder form) of yellow, red, and blue were purchased from Kofar-Mata market Kano, Nigeria. The dye powder was dispersed in hot water and manually stirred using hands until completely dissolved. Thick rubber gloves were worn before the preparation of the dye solution to prevent skin allergic reactions. A piece of the pure fabric was then immersed in the prepared dye solution and allowed to soak for about 20 minutes until the desired colour was achieved. Subsequently, the fabric was removed and squeezed to remove excess dye solution. Lastly, the fabric was rinsed in water and dried. The above procedures were repeated in preparing three different dyed fabrics; yellow, red, and blue. Figure 1 shows the dyeing procedures and samples of the dyed fabrics.

Measurement of Capacitance

The parallel plate method is recommended when measuring the capacitance with low frequency (< 1 GHz) instruments such as LCR meters. Our LCR meter is the DE-5000 by DER EE Electrical Instrument, Taiwan. It can measure the capacitance at 100 Hz, 120 Hz, 1 kHz, 10 kHz, and 100 kHz test frequency. We used the FR4 single-sided PCB as parallel plates. The size of the top plate is 100 $cm^{2,}$ and the bottom is 150 cm^2. The thickness of dyed fabrics was measured from all sides using a digital caliper, and the averaged value was recorded, as given in Table 1. Each dyed fabric was then sandwiched between the PCB plates in a capacitor form to measure capacitance. The size of the fabric dielectric was bigger than the top plate to prevent edge capacitance. Load mass of 2, 3, and 4 kg was placed on the top plate during measurement to minimize the effect of air-gap between dielectric and the plates. Since our dielectric materials are for capacitive ECG electrodes, the experiment was performed for dry and moisturized dielectrics. The essence of this test is to observe the influence of sweat on the dyed-fabric dielectrics. The dyed fabrics were moisturized by placing them on the skin of a sweaty male subject of age 42. Figure 2 shows the measurement setup.

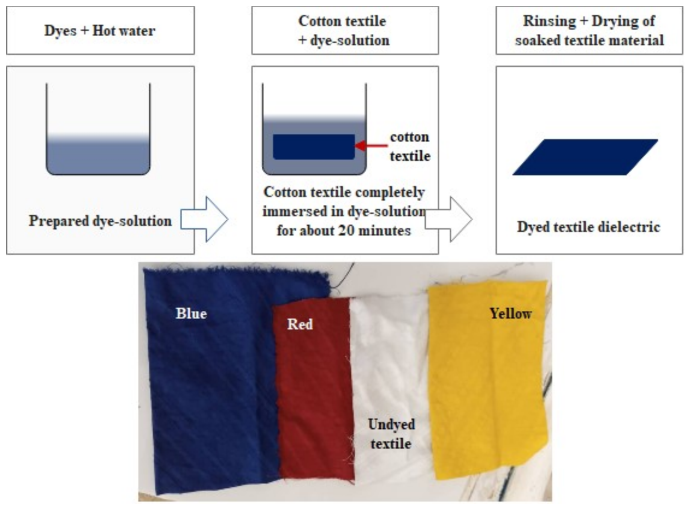

Figure 1. Schematic procedures of dyeing cotton fabric and samples of dyed fabrics.

Estimation of Relative Permittivity

The relative permittivity was calculated from equation (1), which describes the capacitance of the parallel plate capacitor.

$$C = {}^{\varepsilon_o \varepsilon_r A}/_{d} \quad (1)$$

Where C = capacitance (F), ε_o = permittivity of free-space (8.854×10^{-12} F/m), ε_r = relative permittivity, A = size of top-plate, and d = thickness of dyed-fabric dielectric. Tables 1 and 2 show the measured capacitance and relative permittivity estimated for dry and moisturized dyed-fabric dielectrics at the different test frequencies.

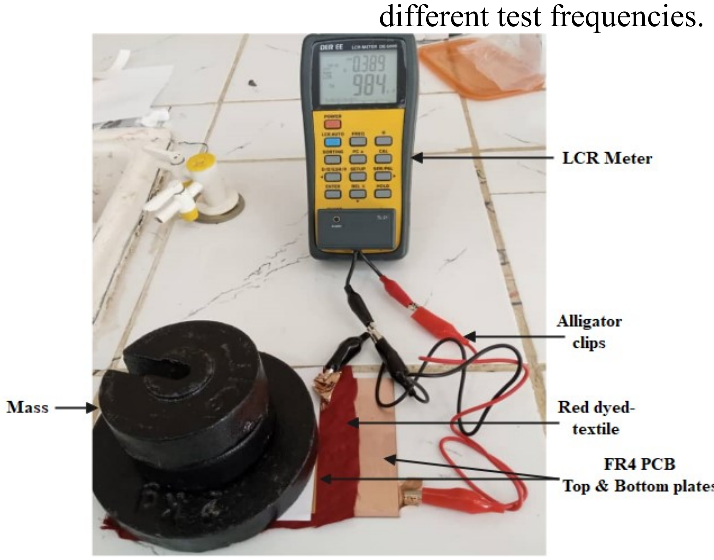

Figure 2. Parallel plate method for measuring of capacitance from a red dyed-fabric dielectrics.

RESULTS AND DISCUSSION

A test has been conducted to determine the impact of dye on dielectric parameters of fabric dielectrics. Tables 1 and 2 present the measured capacitances and relative permittivity calculated for dry and moisturized fabric dielectrics under different pressure and test frequencies. After dyeing, the thickness of the fabrics has doubled. Maximum capacitances were measured at 100 Hz, but the values decreased by about 50 percent at 100 kHz frequency for all fabric dielectrics tested. For instance, in Table 1, dry undyed fabric recorded a capacitance of 1165.00 pF at 100 Hz but 677.70 pF at 100 kHz. In the parallel-plate technique, the air gap between the plates can affect the capacitance. An increase in pressure by adding load mass increased capacitance due to a decrease in the air gap.

Figure 3 shows variation in relative permittivity of the dry fabric dielectrics at the different test frequencies. The relative permittivity for the fabric dielectrics reached a maximum at 100 Hz test frequency when the highest pressure was applied. The undyed fabric has a smaller thickness but measures the highest capacitance. On the contrary, yellow-dyed dielectric yielded the highest relative permittivity (2.34) even though its thickness is twice that of the undyed fabric. A possible cause is that the permittivity, an estimated value not measured, depends on other parameters in the equation. From 100 Hz and 120 Hz, the relative permittivity showed a slight decrease. However, at 1 kHz, the relative permittivity significantly decreased by almost one-third in all the fabrics. This effect was anticipated as the relative permittivity is known to decrease with increased test frequency.

Table 1. Measured capacitances and relative permittivity calculated for dry pure and dyed fabric dielectrics

Fabrics	Mass kg	Fabric thickness mm	Capacitance measured at LCR meter test frequency (pF)					Relative permittivity calculated for pure and dyed fabric dielectrics				
			100 Hz	120 Hz	1 kHz	10 kHz	100 kHz	100 Hz	120 Hz	1 kHz	10 kHz	100 kHz
Undyed	2.0	0.11	1165.00	1135.00	879.80	745.00	677.70	1.45	1.41	1.09	0.93	0.84
	3.0		1268.00	1236.00	943.60	790.30	716.30	1.58	1.54	1.17	0.98	0.89
	4.0		1337.00	1302.00	980.70	816.50	738.10	1.66	1.62	1.22	1.01	0.92
Blue-dyed	2.0	0.20	830.00	804.00	617.40	482.70	417.60	1.87	1.82	1.39	1.09	0.94
	3.0		951.00	925.00	674.70	519.70	446.50	2.15	2.09	1.52	1.17	1.01
	4.0		1026.00	998.00	717.60	548.10	468.20	2.32	2.25	1.62	1.24	1.06
Red-dyed	2.0	0.21	745.00	738.00	533.40	413.60	362.90	1.77	1.75	1.27	0.98	0.86
	3.0		888.00	858.00	603.50	460.20	400.90	2.11	2.04	1.43	1.09	0.95
	4.0		951.00	924.00	643.10	486.50	422.10	2.26	2.19	1.53	1.15	1.00
Yellow-dyed	2.0	0.23	788.00	765.00	560.00	432.40	370.90	2.05	1.99	1.45	1.12	0.96
	3.0		859.00	834.00	598.40	455.10	388.00	2.23	2.17	1.55	1.18	1.01
	4.0		899.00	872.00	619.30	467.90	398.20	2.34	2.27	1.61	1.22	1.03

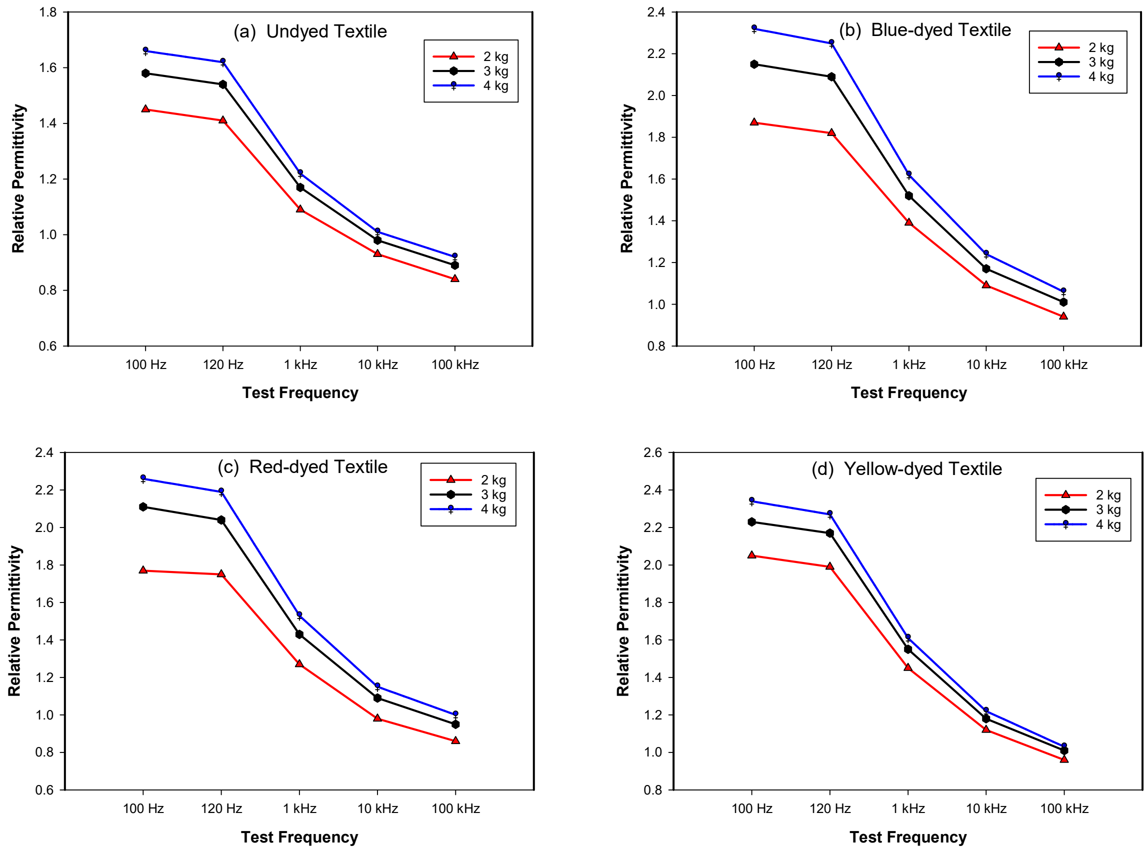

Figure 3. Relative permittivity under varying pressure and test frequency for dry (a) undyed, (b) blue-dyed, (c) red-dyed, and (d) yellow-dyed fabric dielectrics.

When fabric dielectrics are used in long-term ECG monitoring, they get moisturized by skin exudates over time. In capacitive ECG measurement, this could affect the electrode coupling capacitance and its effectiveness (Ueno et al., 2007). Table 2 shows the capacitances measured for moisturized fabric dielectrics. The capacitances measured are higher compared to that of dry dielectrics. For example, at maximum pressure, the moisturized undyed-fabric dielectric recorded 6030 nF at 100 Hz while 1165 pF was measured for dry undyed-fabric at the same frequency. The findings prove that skin exudates strongly influence fabric dielectrics, particularly porous fabrics.

Another is interesting findings is that capacitances measured depend on the thickness of the fabric. Thinner fabrics produced higher capacitances for all pressure and test frequency. These results agree with our expectation since capacitance is inversely proportional to the thickness of the dielectric. This relationship between capacitance and thickness of dielectric can be seen for all the dyed fabrics.

Table 2. Measured capacitances and relative permittivity calculated for moisturized pure and dyed fabric dielectrics

Fabrics	Mass kg	Fabric thickness mm	Capacitance measured at LCR meter test frequency (nF)					Relative permittivity calculated for pure and dyed fabric dielectrics				
			100 Hz	120 Hz	1 kHz	10 kHz	100 kHz	100 Hz	120 Hz	1 kHz	10 kHz	100 kHz
	2.0		3090.00	3370.00	330.00	14.66	0.51	3838.94	4186.81	409.98	18.21	0.63
Undyed	3.0	0.11	6590.00	6130.00	879.50	26.45	0.48	8187.26	7615.77	1092.67	32.86	0.59
	4.0		6030.00	5280.00	545.90	4.79	0.28	7491.53	6559.75	678.21	5.95	0.35
	2.0		2600.00	2370.00	656.40	216.00	37.61	5873.05	5353.51	1482.72	487.92	84.96
Blue-dyed	3.0	0.20	2920.00	2600.00	676.40	161.66	7.07	6595.89	5873.05	1527.90	365.17	15.97
	4.0		3130.00	2830.00	607.60	103.54	2.63	7070.25	6392.59	1372.49	233.88	5.94
	2.0		2000.00	1797.10	497.20	116.00	14.91	4743.62	4262.38	1179.26	275.13	35.36
Red-dyed	3.0	0.21	2260.00	149.70	269.90	480.50	421.21	5360.29	355.06	640.15	1.14	1.00
	4.0		2370.00	2300.00	549.00	119.79	420.70	5621.19	5455.16	1302.12	284.12	1.00
	2.0		2590.00	2500.00	753.60	159.0	9.60	6728.03	6494.24	1957.62	413.19	24.94
Yellow-dyed	3.0	0.23	2030.00	3360.00	779.70	318.50	0.42	5273.32	8728.26	2025.42	827.37	1.10
	4.0		3000.00	3910.00	1121.80	297.60	11.38	7793.09	10156.99	2914.10	773.07	29.56

Figure 4 shows the influence of dyes on the relative permittivity of fabric dielectrics. As can be seen, the permittivity increases with an increase in pressure, reaching a maximum at 100 Hz test frequency, afterward rapidly declining as frequency increases from 120 Hz to 1 kHz. The reason for this phenomenon has been previously explained. Surprisingly, the highest relative permittivity was achieved at 3 kg load mass, except for values obtained for the dyed fabrics. From 10 kHz, the permittivity slowly declined to values below 1. However, the dyed fabrics recorded greater values, with blue-dyed fabrics having the highest permittivity. Some inconsistency in permittivity can be seen despite the increase in pressure. One reason for such inconsistent results is that the moisturized dielectric gradually dries as the experiment is prolonged

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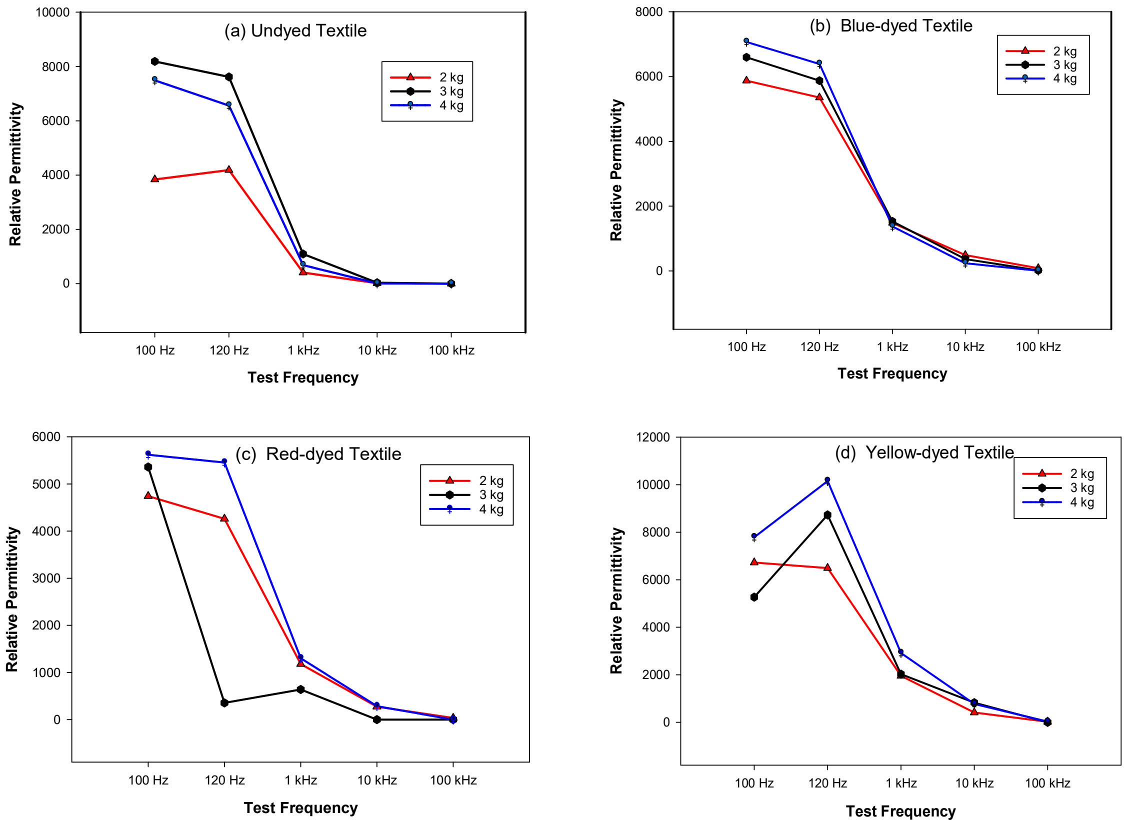

Figure 4. Relative permittivity under varying pressure and test frequency for sweat-moisturized (a) undyed, (b) blue-dyed, (c) red-dyed, and (d) yellow-dyed fabric dielectrics.

The results demonstrated in this study provide evidence that dye has effects on the dielectric parameters of cotton fabrics. The experiment illustrated that thickness, pressure, porosity, skin exudates, and test frequency influence fabric-based dielectrics' capacitance and relative permittivity. Therefore, incorporating cotton fabrics as a dielectric in capacitive ECG electrodes requires understanding and careful selection of materials. Table 3 compares previous results with the current study at 1 kHz test frequency. Higher values were obtained at lower test frequencies, as shown in Tables 1 and 2.

CONCLUSION

This study was conducted to investigate the effects of dye on cotton fabrics used as dielectrics in capacitive ECG electrodes. The experiment used a parallel-plate technique to measure important dielectric parameters such as capacitance and relative permittivity of undyed and dyed cotton fabrics. The results obtained indicate that dye affects the dielectric parameters of fabrics. Dyed cotton fabrics measured higher thickness and relative permittivity but lower capacitance than undyed fabrics in dry and moisturized conditions at different test frequencies. For moisturized fabrics, the dielectric parameters obtained are greater than those of dry fabrics but vary with pressure and test frequency.

Table 3. Comparison of dielectric parameters of fabric dielectrics

Fabric	Thickness (mm)	Measured capacitance at 1 kHz (pF)	Relative permittivity, ε_r	Ref
PVC Fabric	0.24	36.09	5.082	(Ng & Reaz, 2017)
Polyester	0.16	57.04	1.178	
Nylon	0.48	19.72	1.222	
Linen	0.40	77.61	4.007	
Rayon	0.58	67.88	3.118	
Cotton	0.23	101.19	3.004	
Dry Undyed Cotton	0.11	816.50	1.22	Current study
Dry Blue-dyed	0.20	548.10	1.62	
Dry Red-dyed	0.21	643.10	1.53	
Dry Yellow-dyed	0.23	619.30	1.61	

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