

A Characterization of Motion Affecting Pulse Oximetry in 350 Patients

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Abstract

As part of an oximetry research effort in which plethysmographic data were collected from moving patients, a wide variety of patient motion affecting pulse oximetry was observed and characterized by the clinical incidence, type, severity and duration of patient motion. 350 patients were observed for movement in clinical settings, including ICU, SICU, MICU, PICU, NICU, OR and PACU, at 4 hospitals and on an ambulance. 20% (70) of the patients exhibited motion. Half (35) of the moving patients were instrumented to record oximetric, plethysmographic and/or acceleration information.

31% of NICU infants moved compared to only 7% of adults in ICUs. The most common noisy oximetry signals were caused by motion characterized by extending/flexing (/kicking in infants) and by clenching/pressing/rubbing. In infants, these motion types accounted for 53% and 11% of motion, respectively. Less common infant motion types were patient cares, shifting body position and cough/cry. The most common adult motions were equally divided among extend/flex, clench/press/rub, twitch/shake and transport motion types. Extend/flex motions typically demonstrated high plethysmographic waveform modulation (71.5% maximum) and high acceleration. Clench/press/rub motions typically also had high modulations, but low G-force. With one high-G exception, twitch/shake motions had little or no effect on oximetry readings. Less common adult motion types affecting pulse oximetry included cough/cry, strain/posture, tremors and tap/bump. Most recorded motions were aperiodic and short-lived, 62% lasting less than 10 seconds, only 5% lasting over 1 minute. NICU patients made the longest lasting continuous series of motions, while adults made 86% of the motions lasting a second or less.

Implications:

The profile of movement affecting pulse oximetry for the infant hospitalized patient population seems to be different from that of adult patients. For the purpose of testing pulse oximetry performance in motion conditions, adult motion may not fairly represent clinical motion in infants. These data indicate that simulated motions for the purpose of testing pulse oximetry should perhaps include extend/flex/kick and clench/press/rub motion types, representing common relevant clinical motions of high and low acceleration force, respectively.

Keywords

oximeter, oximetry, motion, movement, plethysmograph

Background and Purpose

Patient movement has been known to interfere with the ability of pulse oximeters to measure arterial oxygen saturation (1—4). Various researchers have tested oximetry performance using mechanically or autonomously generated motions to simulate hospitalized patient movement (5—40). The relationship of these methods to clinical motion affecting pulse oximetry has been, at best, anecdotally established. Of studies published since 1990 that were surveyed, 10 evaluated hospitalized patients and 36 employed laboratory methods (5—51). Four of the laboratory research groups used mechanical fixtures, four used voluntary movement and four used a combination of the two.

Plethysmographic and accelerometric data from moving patients were obtained in a research engineering effort to develop and test new pulse oximeters able to accurately read saturation despite patient motion. The pulsatile, plethysmographic waveforms comprise the raw input signals for pulse oximetry; the irregular ones recorded from moving patients were used to create oximetry algorithms and played back to test improvements. As these data were collected, a wide variety of patient motions were observed in clinical settings.

A characterization of the types, incidence, duration and severity of the motion observed was made with the intention of adding clinical relevance to the simulated patient motion conditions of methods for testing pulse oximetry performance.

Methods

Institutional review board permission for noninvasive pulse oximetry research was obtained from four hospitals. 350 patients monitored by pulse oximetry in the normal course of treatment in eight clinical settings were observed for movement. Observation was made as a cross-section at a point in time as each site was visited. “Motion” or “movement” is considered here as the kinetic action that may interfere with an oximeter’s ability to clearly read an arterial plethysmographic waveform. Actions which may interfere with oximetry such as partial removal of the sensor or pulsation reduction (e.g., by blood draw or occlusion) are not considered “motion” for the purpose of this discussion. Innocuous, minor or short-lived actions, which have no visible affect on the plethysmogram, are not considered here to be “motion” or “movement.”

35 of the patients observed to move were instrumented with additional oximetry for plethysmographic data collection. When possible, a third, reference oximeter monitored a non-moving site on the patient. A small accelerometer (Crossbow Technology model CXL04M3) was attached near the sensor site on 22 of these patients. The accelerometer measured the change in its speed in terms of G-forces in three orthogonal directions. After collection, the three-dimensional values were corrected for offsets and combined into a net acceleration value. Portable computers stored the plethysmographic, oximetric and accelerometric data in sets of corresponding files.

Approximately 14.5 hours of data were recorded from the 35 patients. The collection averaged 25 minutes per patient, although the maximum recorded from one patient was over 90 minutes of data. During collection, observational notes recorded the types and times of motion and relevant ambient conditions. These sets were further broken down around the motion contained into more manageable

file sizes typically, 3 minutes in length. 218 sets of these files were processed and analyzed; 698 events of continuous motion were registered. The motion sections of these files were listed in a database showing type and duration of each motion event, maximum percent modulation of the infrared channel and maximum G-force. These files were also correlated with waveform analysis and the observation notes.

Percent modulation is an indicator of pulsatile signal strength in nominal oximetry conditions, but in signals affected by motion, percent modulation is a measure of the noise on the signal. That is, interference from motion or other sources may cause the signal to vary greatly relative to the basic amplitude of the signal. The percent modulation of the infrared channel was determined from playback of the recorded signal.

Results: Clinical Sites and Incidence of Motion

Of the 350 patients observed, 70 patients (20%) demonstrated motion. Data were collected from 35 of these patients (10% of all patients observed; 50% of the moving patients). Some active patients were not monitored by oximetry and thus were not included in the study. 15 patients were pulmonary rehabilitation exercise patients. All 15 of the pulmonary rehabilitation patients moved because they were exercising, either on treadmills or stationary bicycles. All were adults, typically over 60 years of age. They were checked by pulse oximetry if not monitored continuously. Discounting for the exercise patients, 55 of 335 patients (16%) observed in clinical settings demonstrated motion. The clinical settings included various intensive care units (ICU, by type: neonatal, pediatric, medical and surgical), operating room (OR) and a post-anesthesia care unit (PACU). See Table 1.

Table 1. Moving Patients by Clinical Setting

Setting	Number of Sites	Patients Observed	Patients Moving	Percent Moving
NICU	2	123	38	31%
PICU	1	3	1	33%
MICU	2	42	1	2%
SICU	2	121	10	8%
OR	1	1	1	100%
PACU	1	41	1	2%
Ambulance	1	4	3	75%
Total		335	55	16%

Of the hospitalized recumbent patients who moved, 73% of were infants and 27% were adults. Of infants in intensive care, 31% were observed moving compared to only 7% of the adults in intensive care. Only one of the post-operative adult patients was observed moving. Only one adult in surgery was observed: the patient was specially noted by the anesthesia staff as moving and motion data were collected. None of other dozens of patients in the OR at that site were reported to be moving. While OR patients were not monitored by oximetry when they were rolled or transferred from table to gurney, perhaps all would exhibit motion at that time. All three of the subjects transported by ambulance showed motion due in part to the transport; another patient seen was not transported and

was not moving. A few patients were observed and counted more than once as they remained in a particular unit on separate days.

Results: Types of Motion

The many forms of motion demonstrated by patients were grouped into the categories shown in Table 2. Most movements were self-generated, but many were caused by external forces, e.g. transport. Since sensors were always on an extremity, most movements were caused by a movement of the extremity, e.g. reach. Many other motions, however, were caused by a movement of the whole body.

Table 2. Types and frequency of motions observed.

ADULTS			Percent		INFANTS	
Motion Type	Periods	of Total	Periods	of Total	Motion Type	
Twitch/shake	101	21%	208	53%	Extend/flex	
Transport/external force *	96	20	57	15	Twitch/shake	
Clench/press/rub	88	18	55	14	Transport/external force	
Extend/flex	73	15	44	11	Clench/press/rub	
Exercise motions *	41	8	18	5	Shift own body position	
Shift own body position	35	7	8	2	Cough/cry	
Cough/cry	20	4	3	1	Anomalies	
Strain/posture	14	3	0	0	Exercise motions	
Tap/bump	14	3	0	0	Strain/posture	
Anomalies	3	1	0	0	Tap/bump	
Total Periods:	485	100%	393	100%		

More than half (53%) of the infant motions observed fell into the category of extending/flexing motions. Extending/flexing motions characteristically resulted in both high percent modulation and high acceleration. The extending/flexing category included reaching, waving, kicking, swinging, pulling/retracting, rotating at the elbow or knee, flexing at the wrist or ankle and lifting the extremity (and often dropping it or letting it settle). These movements were typically aperiodic and seemed to occur at random. Infant patients demonstrated a wider variety within this type of motion than did adults, in part, because the sensor site was as likely to be on the foot as it was on the hand. Moving infants often exhibited extending/flexing motions in sequence with clenching/pressing motions.

The twitching/shaking category includes motions described as shivering and tremors among adults and jerks among infants. While twitching/shaking motions were common, they tended to have less of an effect on pulse oximetry than other categories (with one exception; see Figure 2) resulting in either lower percent modulation or much shorter durations. Anxiety, cerebral dysfunction, Parkinson’s disease and motor-chemical imbalances were typically associated with these motions in adults. In some situations, temporary moisture obstructions in ventilator tubes resulted in a spasm of the whole body. Infants exhibited unpredictable and quick, seemingly autonomous jerks of an entire arm or leg.

* These data include ambulance transport and/or exercise settings and, therefore, do not fairly represent the percentage of movement of hospitalized recumbent patients.

Common motions that tended to apply direct force to the sensor were described as clenching, pressing, rubbing, squeezing, scratching, dragging, grasping or bending. While these motions often resulted in high percent modulation and distorted waveforms, they typically were not associated with high acceleration. Adult patients typically pressed, dragged or rubbed the sensor against their thigh, the mattress or rails and grasped cords, sheets or rails. Similar sorts of adult motions classified separately were randomly bumping the monitored hand or using it to tap with. Both adults and infants attempted to clench their hands closed into fists with the sensors on finger/hand sites. Adults bent fingers where sensors were attached, and infants typically scrunched their feet. Infants also bit the sensor site and made crawling motions with the sensor. Wraps mitigate the extent of motion in infant patients, but they may mask kicking or pressing that affect the pulse oximeter.

Motions caused by forces external to the patient included actions such as a nurse adjusting the patient as well as patients being transported. Adult transport motion was collected in the back of a speeding ambulance and included bumps and changes in acceleration. Less dramatic motion data were collected as beds were tilted or patients were prepared and given injections. ICU patients were rolled and held during bedding and dressing changes. NICU patients were picked up, put down, rolled over and held while cares were given such as feeding, burping, massaging of the tear ducts and percussion of the lungs.

Patients often shifted their position in their beds, chairs or isolettes, and these motions were grouped as such into a separate category when the adjustment did not qualify as a single specific motion such as pressing, pulling or grasping. Similarly, exercise data were collected on adult pulmonary rehabilitation patients who were either using a treadmill or stationary bicycle. The fingers were monitored either holding on to a handlebar (which moved in the case of the bicycle) or not touching anything, either unsupported or using the other fingers to grasp the bar.

Data were collected from several patients who demonstrated motion as a result of coughing. Similarly, some infant patients moved as a result of crying, hiccups or yawning. Val salva motions were included under the straining and posturing category. Motions in this category were typically seen when adults extended their hands or fingers in spite of wrist restraints or when they would rigidly pose their hands or fingers.

Results: Strength of Motion

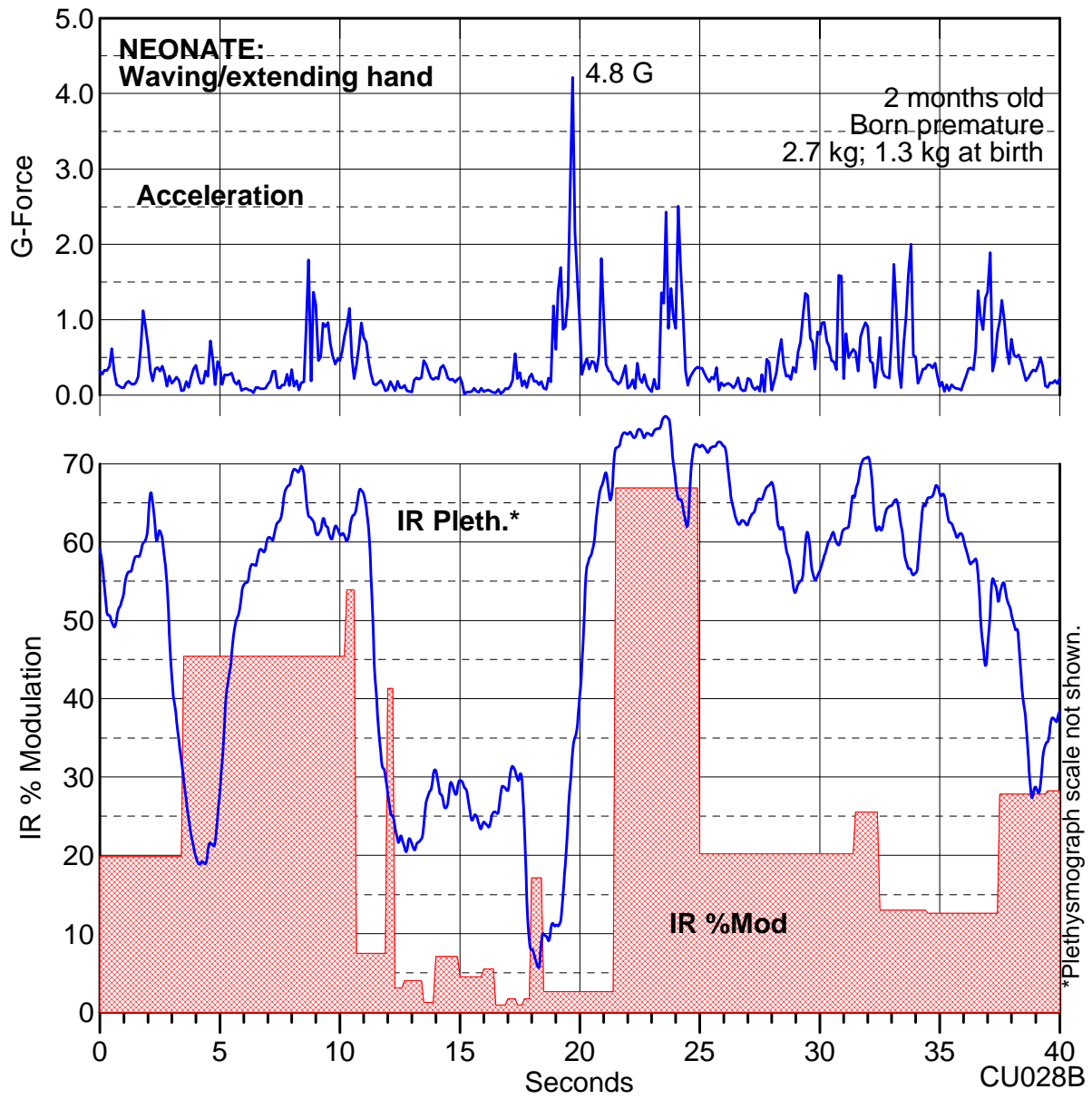
The strength of motion was characterized primarily by the percent modulation of the infrared signal. The noisiest 6% of data sets were all collected from infants, and all involved waving, extending, pulling and/or clenching. See Table 3. The greatest percent-modulation (71.5%) was seen in an infant patient performing a clenching/waving motion. No corresponding accelerometer data were collected on this patient.

Table 3. Noisiest motion data sets.

Maximum %Modulation	Maximum G-force	Duration (seconds)	Motion Description	Patient
71.5		67	Clench/wave	infant
68.2		26	Extend	infant
67.0		16	Wave/extend	infant
66.9	4.8	92	Wave/extend/yawn	infant
64.0		70	Wave/extend/shake	infant
61.9		13	Clench	infant
61.7		8	Pull	infant
60.2	5.2	165	Wave/extend	infant
58.2		34	Extend/grasp	infant
56.0	4.5	73	Wave	infant
55.6		21	Pull/extend	infant
55.0	4.5	120	Wave	infant
48.9	2.3	48	Wave	infant
46.4	1.3	7	Cough	adult
42.6	0.5	11	Twitch/rotate/lift/drop	infant
42.3	4.4	60	Extend/wave	infant
42.0	1.9	26	Body-lift	infant
41.6	5.1	24	Roll	adult

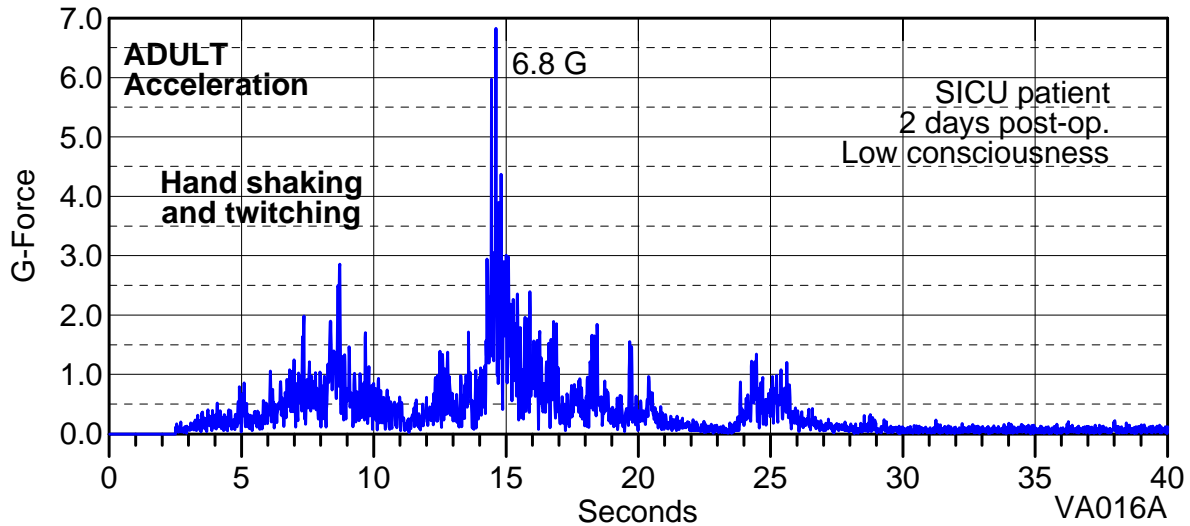
The first 40 seconds of one of the noisiest motion sets collected are shown in Figure 1. The motion in this set lasted for 92 seconds with a maximum modulation of 66.9%. The top part of the figure shows the accelerometer trend. Below, the percent modulation is trended with the plethysmographic waveform. The plethysmographic waveform is not to scale nor is it adjusted to scale. Note the apparent coincidence of the motion recorded by the accelerometer with the change in the plethysmographic waveform. The waveform is so distorted by the motion that the underlying plethysmogram is barely discernable.

Figure 1. Example of noisy motion trend.



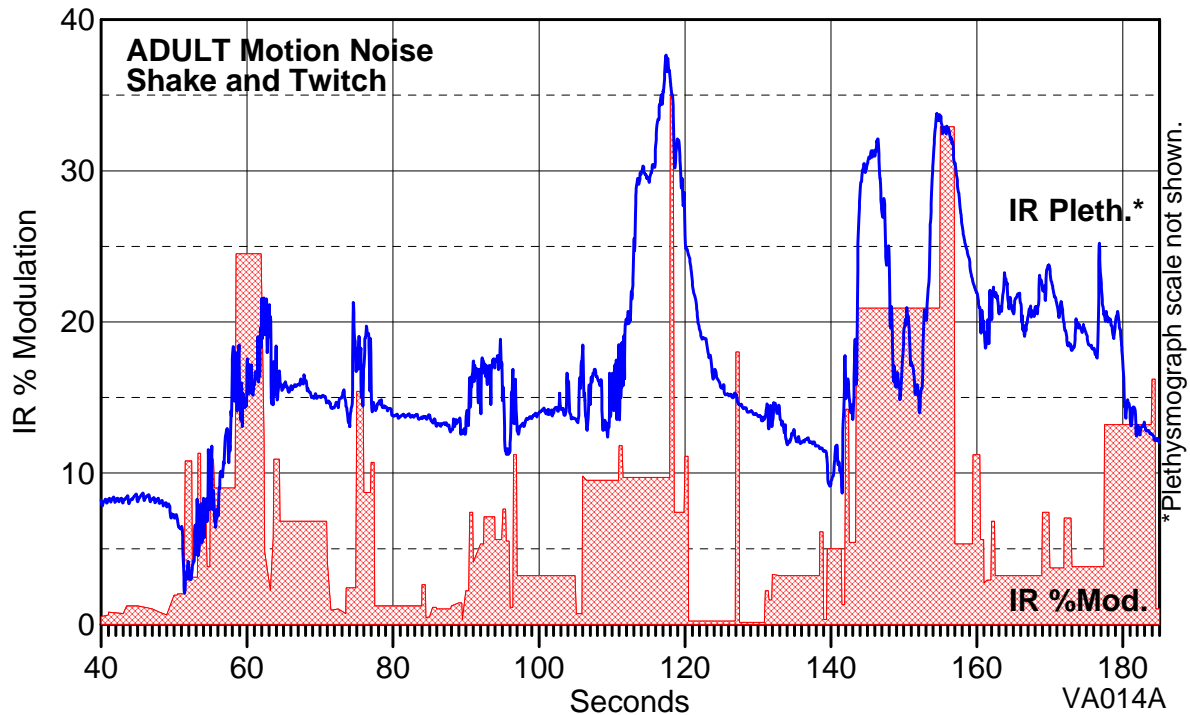
The greatest acceleration recorded (6.8 Gs) was when an adult SICU patient's hand shook and twitched during gastrointestinal tube placement. See Figure 2. The corresponding infrared modulation was 9%, less than the mean (19%) of the maximum values for all data sets.

Figure 2. Trend showing maximum acceleration recorded.



Minutes earlier, the same patient demonstrated one of the longer, noisiest periods. See Figure 3. This nearly violent motion occurred before the accelerometer could be attached. Typical modulation for the study during quiescent periods was 1.5—6% and typical acceleration 0.1—0.5G.

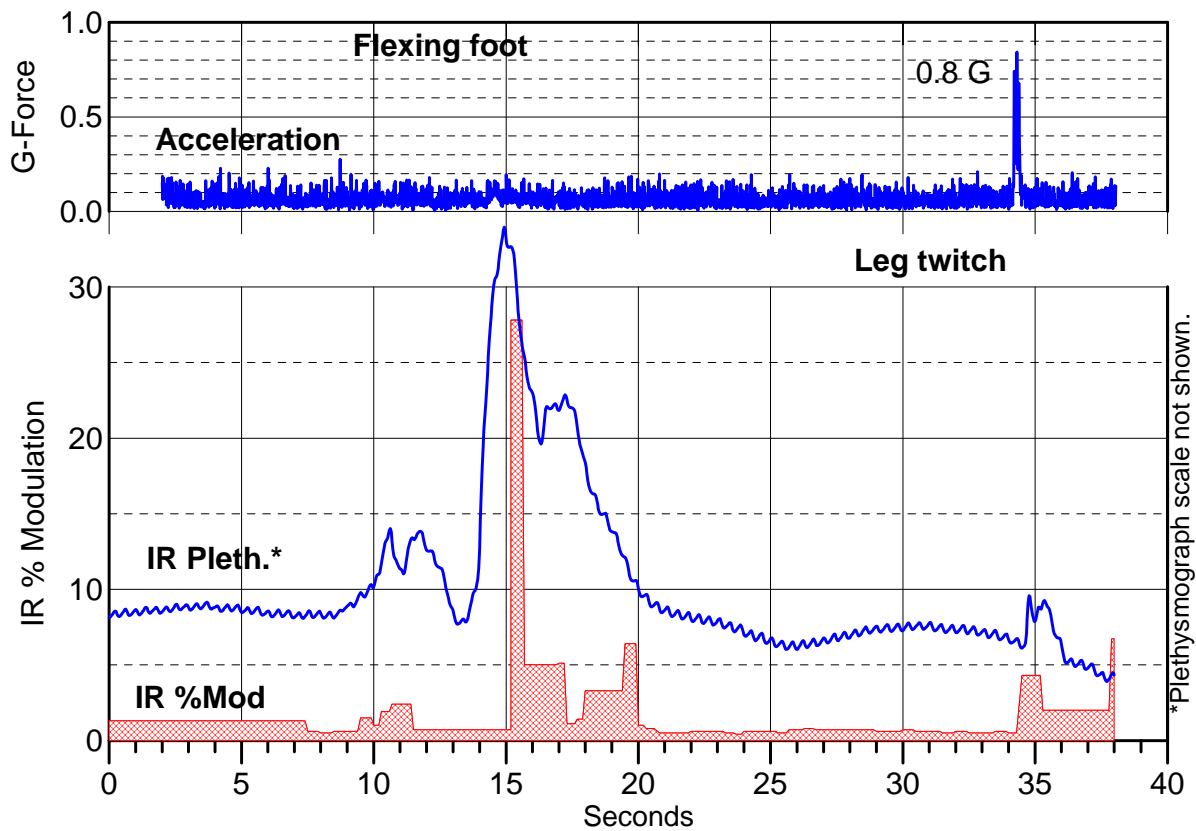
Figure 3. Trend showing high percent modulation and plethysmographic waveform.



The signal did not necessarily require large amplitude changes, that is, increases in percent modulation, to register noise from motion. Motion was also registered by the distortion of the plethysmographic waveform. One of the noisiest signals came from a hand resting on the edge of a bench in the rear of an ambulance travelling at 60 mph on a bumpy highway.

Figure 4 shows a clear example of oximetry motion that was only partially correlated to the force of physical motion. In this case, when the infant patient flexed their foot, little or no movement was detected by the accelerometer, but the oximeter was dramatically affected. The plethysmograph was deformed and the modulation rose to 28%. In a quicker, larger motion, the patient's leg twitched, and a 0.8-G motion was detected by the accelerometer. A less dramatic perturbation of the waveform resulted, however, with a modulation of only 4%.

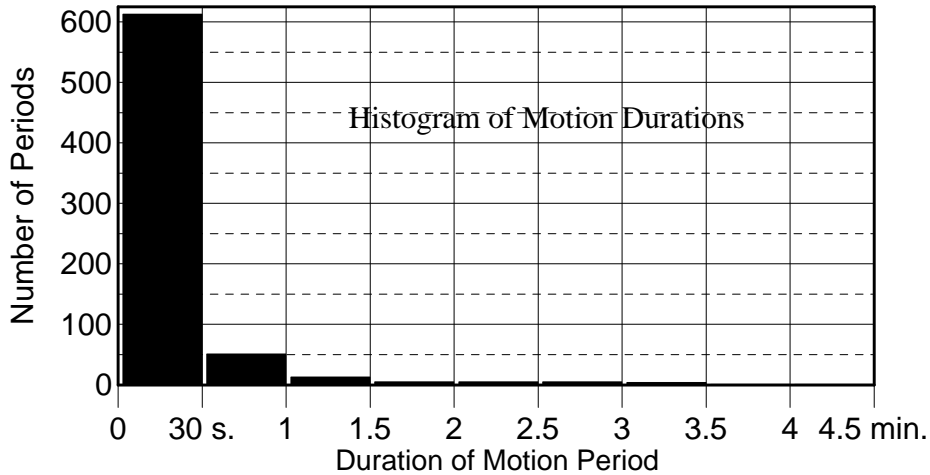
Figure 4. Example of plethysmographic trend showing partial correspondence to accelerometer values.



Results: Duration of Motion Periods

Most motions collected were short-lived, typically lasting 5 seconds or less (37%). 62% of motion periods lasted 10 seconds or less with 88% lasting 30 seconds or less. Less than 5% lasted over a minute (34 of 698 motion periods collected). The longest period of motion during which no clear signal could be discerned lasted 260 seconds.

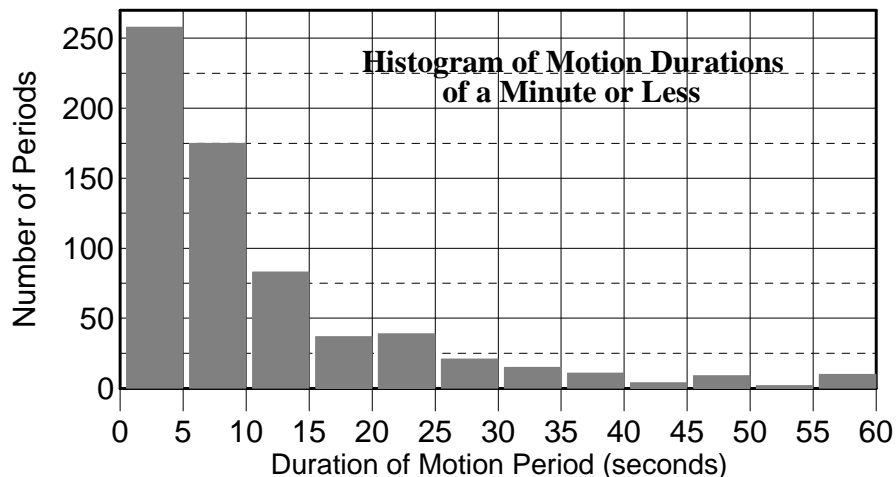
Figure 5. 88% of motion periods lasted 30 seconds or less.



The shortest motions were less than a second in duration. These motions typically were a single cough, a tap, a twitch or a shake, a quick lift of the hand or a brief strain.

Most short motions lasting a second or less were from adults. Most of the motions lasting longer than a minute were from infant patients. Some of the quicker infant motions occurred in conjunction with other, longer motions. Only 5 of 36 (14%) periods of continuous motion lasting a second or less were from infant patients.

Figure 6. Most motion periods lasted 10 seconds or less.



The longest motions were typically combinations of motion types. The longest motion was an infant extending and pulling their hand back in a continuous action as if waking up. The next three longest motions — and 10 of the 15 longest motions — were also on infant patients. Table 4 shows the type of motion and patient for each of the 15 longest continuous motion periods.

Table 4. Longest Recorded Clinical Motion Periods.

Seconds	Patient	Type of Motion
260	infant	extend/pull, as if waking
240	infant	clench/extend, wave/extend, bite
210	infant	extend, roll, wave/rotate
200	infant	wave/cry, extend, rotate, cough/jerk/pull
200	adult SICU	shake/twitch, val salva, bump
190	infant	percussion, extend/rotate, body-lift, wave/cry
180	adult SICU	shake/twitch
179	adult ambulance	transport: bumps, decelerate, accelerate
174	infant	percussion, shake, pull, extend, body-lift
171	infant	wave/extend, flex/wave
165	infant	wave/extend, breathing
150	adult exercise	treadmill
146	infant	adjust, extend, feed
143	infant	yawn/shift, extend/wave, adjust/shift/extend
138	adult SICU	twitch, shake

Discussion

A characterization of the types, incidence, duration and severity of the motion observed was made with the intention of adding clinical relevance to the simulated patient motion conditions of methods for testing pulse oximetry performance.

The statistics given for duration, strength and types of motion only represent those motions during which data were collected. Much more motion was *observed* than collected, but they tended to be the same sort of motions as those collected. Emphasis was placed on the incidence of motion in hospitalized recumbent patients monitored by pulse oximetry. Less representative data were collected in ambulance transport and in pediatric medicine.

Clinical motion patterns were found to be irregular in nature. Infant and adult patient populations had significantly different profiles of motion affecting oximetry. Infants had more motion, longer periods of motion and motion that was more intense. Adult patients had less motion, shorter periods of motion and less intense motion.

The worst motion for oximetry was not necessarily when the physical movement was greatest. Clenching and pressing were typically motions that resulted in high percent modulation and distorted signals but low G forces. Extend/flex/kick motions, the most common among infants, tended to have the greatest effect on both percent modulation and the accelerometer. These two common motion categories accounted for most of the noisiest oximetry signals.

The low correlation of physical movement with oximetry signal noise is partly the result of the inability of measuring acceleration at the exact site of the detector. More importantly, there are motions that are noisy for oximetry which can be subtle in size and speed. It was clearly observed that small movements, such as clenching of a finger or foot, resulted in as much pulse oximeter inaccuracy as did sudden movement changes. Clenching/pressing/rubbing motions may cause irregular compression of the vascular bed between the emitter and detector of the oximetry sensor. Conversely, sudden acceleration observed in other motion types may distort the vascular bed and, therefore, the light passing through it in a different way.

From these data we infer that to accurately represent hospitalized recumbent patient movement, types of movement that distort the vascular bed during low acceleration conditions are as significant as movements that create a sudden acceleration change. In our opinion, the two motion categories that best represent this dichotomy are extend/flex/kick and clench/press/rub. These types were the two most commonly observed categories of motion that significantly affected pulse oximetry in the hospitalized recumbent patient. Extend/flex/kick and clench/press/rub easily lend themselves to laboratory tests that involve volunteer subjects. Furthermore, due to the substantial differences between the adult and infant populations, oximetry performance testing using adults may not sufficiently represent oximetry behavior in the infant population.

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